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Plant diversity and community characteristics in the intake area of the South-to-North water diversion project canal in Nanyang City

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The Middle Route of the South-to-North Water Diversion Project is a core national strategic water transfer infrastructure of China; intact natural woodland at intake sites is essential to purify inflow water, conserve water resources and sustain long-term ecological security of the whole water diversion system, which necessitates systematic woodland biodiversity investigation. The SNWDP is a major national strategic water project in China, and its intake area plays a key role in water security and ecological protection. To clarify plant diversity and community characteristics in the intake area of the SNWDP Canal in Nanyang City, 12 standard sample plots were set up in Xixia, Neixiang, and Xichuan counties. We systematically investigated the tree, shrub, and herb layers using stratified sampling. A total of 122 higher plant species belonging to 55 families, 108 genera were recorded. *Quercus variabilis* was the absolute dominant species in both the tree layer and shrub layer, while *Carex breviculmis* dominated the herb layer. Two national Class II protected plant species (*Emmenopterys henryi* and *Cymbidium goeringii*) and two invasive alien species (*Erigeron sumatrensis* and *Bidens pilosa*) were found. Species diversity followed the order: shrub layer > herb layer > tree layer. The tree layer was dominated by young and middle-aged individuals, indicating that the community is in the mid-successional stage. This study provides basic data and a scientific reference for water-source forest conservation, biodiversity protection, and ecological restoration in the SNWDP intake area.

KEYWORDS
community structure, ecological conservation, plant diversity, South-to-North water diversion project, water source area

1 Introduction

Forest ecosystems provide irreplaceable ecosystem services worldwide, especially water conservation, climate regulation, soil protection, and biodiversity maintenance (Adeniyi et al., 2026; Cord and Wätzold, 2026). For large-scale water diversion projects, forests in water-source areas act as ecological barriers that directly determine water quality, supply stability, and regional ecological security (Yutong and Lingling, 2024; Dudov et al., 2026).

Well-structured forests enhance infiltration, reduce runoff, filter non-point source pollution, and sustain long-term watershed health (Kai et al., 2025; Coppieters et al., 2026).

Human activities and climate change have placed growing pressure on forest ecosystems, leading to habitat fragmentation, simplified community structure, and degradation of ecological functions (Gao, 2025; Xu and Wang, 2026). These changes threaten the integrity and stability of water conservation forests, especially in ecologically sensitive regions (Pengzhen, 2022; Yu et al., 2026). Baseline vegetation surveys are therefore critical for evidence-based conservation and restoration (Depo and Mingzhe, 1991; Junce, 2018).

Henan Province lies in the climatic transition zone between subtropical and warm temperate regions, supporting rich forest types and high plant diversity (Depo and Mingzhe, 1991; He et al., 2025). Located in central China geographically, Henan Province boasts abundant endemic and rare wild plant resources; more than 130 provincial endemic vascular plant species and over 65 national key protected wild plants have been documented across mountain areas such as Funiu and the Tongbai Mountains, forming important regional germplasm resource pools for plant conservation in central China. Relevant long-term vegetation research has continuously proved the irreplaceable conservation value of local natural forests.

The South-to-North Water Diversion Project (SNWDP) is one of the largest inter-basin water diversion projects in China. The Middle Route originates in Nanyang City, Henan, and serves as a core national strategic water source affecting tens of millions of people (Wei and Li, 2023; Yutong and Lingling, 2024; Yizhan, 2025). The ecological condition of its intake area is therefore critical to the safety and sustainability of the entire project (Sun et al., 2022; Yizhan, 2025) (Figure 1).

Despite its importance, this region has long been affected by engineering construction, agricultural activities, and human disturbance, resulting in simplified forest structure, loss of native species, and reduced ecosystem services (Pengzhen, 2022; Qi et al., 2025; Seel et al., 2025). Previous studies have documented vegetation composition, community structure, and biodiversity in the Funiu Mountains, the Tongbai Mountains, and Danjiangkou Reservoir area (Junce, 2018; Sun et al., 2022). However, targeted and systematic research on plant diversity in the highly sensitive canal intake area remains limited (Lei, 2020; Luo et al., 2026).

Most existing studies focus on water quality, land use, and hydrological modeling rather than forest plant communities (Sun et al., 2022; Gao, 2025). As a result, substantial knowledge gaps remain in species composition, diversity patterns, and community structure of water-conservation forests in the core intake zone (Lei, 2020; Luo et al., 2026; Yu et al., 2026).

This study conducted a comprehensive field investigation in the intake area of the Middle Route of the SNWDP. We analyzed species composition, plant diversity, community structure, dominant species, protected plants, and invasive plants. The objectives were to reveal the ecological characteristics of regional forests, identify key conservation targets, and fill data gaps for evidence-based management. The findings provide a scientific basis for forest conservation, ecological restoration, and biodiversity maintenance in strategic water-source areas and support the long-term safe

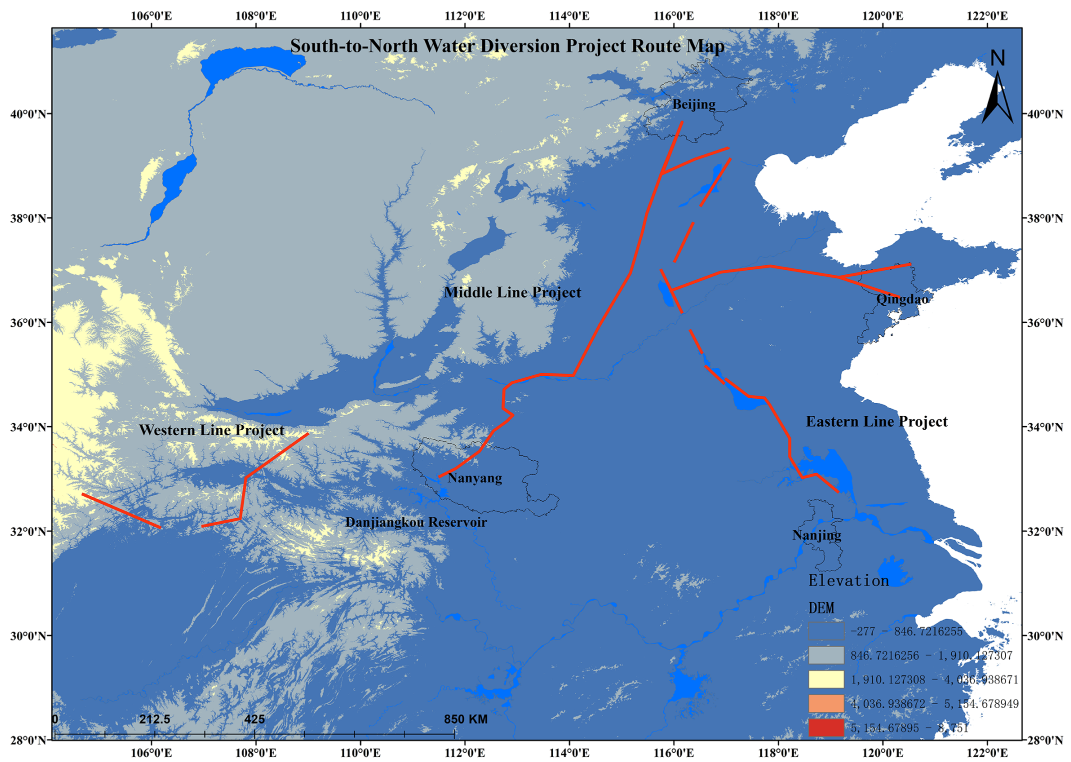

FIGURE 1
The three routes of the South-to-North water diversion project canal.

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operation of the SNWDP (Lei, 2020; Yutong and Lingling, 2024; Yubin, 2025; Luo et al., 2026; Yu et al., 2026).

2 Materials and methods

2.1 Overview of the study area

Nanyang City is the core water source area of the Middle Route of the SNWDP. It has typical north-south transitional monsoon climate, which integrates the climatic characteristics of subtropical and temperate zones and forms a unique transitional vegetation climate condition, complex landforms, typical temperate deciduous broad-leaved forests, frequent human activities, and high ecological sensitivity, making it an ideal area for plant diversity and community structure research (Depo and Mingzhe, 1991; Sun et al., 2022).

The study area is located in Nanyang City, Henan Province, characterized by a stepped terrain that descends from the northwest to the southeast. The geomorphology is diverse, comprising mountains, hilly terraces, and plain depressions with moderate topographic relief. Situated in a monsoonal transition zone between subtropical and warm temperate climates, the region experiences four distinct seasons and moderate hydrothermal conditions, with annual sunshine ranging from 1,800 to 2,100 hours, an average temperature of 14.4–15.7 °C, and a frost-free period of 220–240 days. Annual precipitation averages 800–1,000 mm; however, its distribution is uneven, peaking between June and August. The climate remains mild and humid, with relative humidity staying between 70% and 80% year-round. These conditions support abundant plant resources, including a wide variety of higher plants utilized for timber, oil, medicine, and fiber. While the vegetation is dominated by temperate deciduous broad-leaved forests, it also includes subtropical components and a rich diversity of rare or endangered species. The complex community structures and high species diversity indicate a habitat well-suited for vegetation development.

In this study, 12 representative sample plots were established in Xixia, Neixiang, and Xichuan counties using a purposive sampling design. The plots were deliberately selected to cover a wide range of environmental gradients, including elevations from 313 m to 759.5 m, varied slope aspects, and different slope positions. This habitat heterogeneity was intentionally considered in the study design to enhance the representativeness and generality of the findings. The spatial arrangement of plots reflects the main habitat types in the water intake area, ensuring that the results are representative and widely applicable to regional forest ecosystems (Table 1).

2.2 Plot setting

Centered on the midpoint of the forest ecological quality plot, a monitoring area of approximately 12.56 km^2 was established with a 2 km radius. The primary plot size was 10,000 m^2 (100 m × 100 m), within which three quadrat groups were arranged. Each group consisted of nested quadrats for different vegetation layers: 20 m × 20 m for trees, 5 m × 5 m for shrubs, and 1 m × 1 m for herbs (Figure 2) (Owers et al., 2026; Wang et al., 2026).

2.3 Investigation methods

In this study, a stratified quadrat method was employed to conduct a systematic investigation of the tree, shrub, and herb layers across 12 forest plots. Simultaneously, specialized surveys were completed to assess environmental indicators, including litter, biomass, and species composition. Strict quality control measures were implemented throughout the entire process. The survey methodology was conducted as follows:

For the tree layer survey, all individuals within the 20 m × 20 m quadrat with a diameter at breast height (DBH) ≥ 5 cm were recorded. Data collected for each individual included species name, individual count, DBH (measured at 1.3 m above ground), tree height, and crown width. Canopy closure was calculated using CAN-EYE software based on photographs taken with a fisheye lens at five sampling points: the quadrat center and four points located 7 meters from the center in the cardinal directions

TABLE 1 General characteristics of the sample plots in the study area.

Plot number	Counties	Longitude/°	Latitude/°	Elevation/m	Slope aspect	Slope position	Slope gradient
1	Xixia	111.57	33.35	419.00	West	Middle slope	16~30
2	Neixiang	111.91	33.35	352.30	North	Lower slope	0~2
3	Neixiang	111.88	33.45	567.80	Southwest	Lower slope	16~30
4	Xichuan	111.33	32.87	458.90	Northwest	Middle slope	31~45
5	Xichuan	111.54	33.03	311.50	North	Lower slope	16~30
6	Xichuan	111.36	33.18	459.80	Southwest	Lower slope	16~30
7	Xichuan	111.56	33.19	313.00	Southwest	Lower slope	16~30
8	Xixia	111.19	33.37	759.50	Southwest	Lower slope	31~45
9	Neixiang	111.78	33.34	337.20	Southwest	Upper slope	16~30
10	Neixiang	112.15	33.32	570.30	Southwest	Ridge	16~30
11	Xixia	111.17	33.52	660.10	South	Middle slope	16~30
12	Xixia	111.41	33.53	572.00	Southwest	Middle slope	16~30

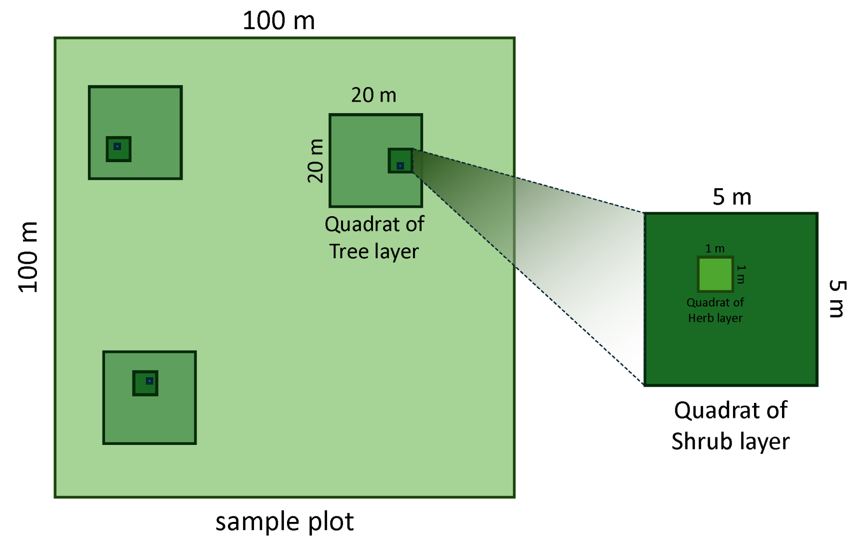


FIGURE 2
Schematic diagram of the quadrat design at the experimental site.

(Weiss et al., 2008). Additionally, three 1 m × 1 m sub-quadrats were randomly established within each 20 m × 20 m quadrat to measure litter thickness and fresh weight, with dry weight subsequently determined after oven-drying at 65 °C (Kai et al., 2025; Xu and Wang, 2026).

For the shrub layer survey, all shrubs and tree seedlings with DBH< 5 cm were recorded within a 5 m × 5 m quadrat. Data collected included species names, abundance, basal diameter, height, clump width, and species-specific coverage (Minxian et al., 2022; Mammo et al., 2025).

For the herb layer survey, species names, abundance, plant height, coverage, and life forms were recorded within each 1m × 1m quadrat. Above-ground biomass was measured by fresh weight and subsequently oven-dried to determine dry weight (Qi et al., 2025; Wang et al., 2025). Concurrently, the occurrence and individual counts of invasive alien species and protected species were identified and accurately documented (Adeniyi et al., 2026; Chen et al., 2026).

Species identification was strictly based on the Flora of China and the Catalogue of Life China, while invasive alien species were identified in accordance with the List of Invasive Alien Species under Key Management. Field data were recorded simultaneously using paper forms and an ecological quality monitoring application, supplemented by photographs of plot features and species characteristics watermarked with longitude, latitude, and dates. A hierarchical data review system was implemented to ensure consistency between paper and electronic records, with data accuracy further verified through sample audits of the plot survey results.

2.4 Data analysis

Based on the plant quadrat survey data and in accordance with the Technical Guidelines for Biodiversity Monitoring—Terrestrial Vascular Plants (HJ 710.1—2014: HJ refers to the industry standard code of China Ministry of Ecology and Environment), biodiversity was quantified using the Simpson Index, Shannon-Wiener Index, Evenness Index, and Composite Diversity Index (Yan et al., 2024; Adeniyi et al., 2026; Cord and Wätzold, 2026). The following formulas were used for calculations:

Simpson Index:

$$D = 1 - \sum P_i^2$$

Shannon-Wiener Index:

$$H' = -\sum P_i \ln P_i$$

Evenness Index:

$$J = -\sum P_i \ln P_i / \ln S$$

Composite Diversity Index:

$$Qi = \sqrt{\sum_{j=1}^{n} a_i},\ a_i = X_{ij}/X_{jmax}$$

In the formula:

*P*i represents the relative abundance of species, calculated as the ratio of the number of individuals of that species to the total number of individuals within the sample plot.

S represents the total number of species recorded in the plot.

Qi represents the comprehensive score, X_{ij} represents the average value of an indicator, X_{jmax} represents the optimal value of an indicator, and n represents the number of evaluation indicators.

The importance value (IV) of each species was calculated using specific formulas tailored to the characteristics of different vegetation layers. For the tree layer, the importance value was defined as (relative abundance + relative dominance + relative height)/3. For the shrub and herb layers, it was calculated as (relative abundance + relative coverage + relative height)/3. Relative dominance for trees was determined based on the basal area at diameter at breast height (DBH), while relative coverage represented the proportion of a species' coverage relative to the total coverage of its respective layer.

Correlation analysis was employed to explore relationships among environmental indicators, including litter, biomass, and coverage. Principal component analysis (PCA) was applied to reveal habitat heterogeneity and community differentiation patterns across the 12 sample plots. One-way analysis of variance (ANOVA) was performed to test the significance of differences in environmental quality indicators among plots, with the significance level set at $P< 0.05$ was used to test the significance of differences in environmental quality indicators among plots, with the significance level set at $P< 0.05$. All statistical analyses were performed using SPSS 26.0.

3 Results and analysis

3.1 Analysis of species composition and importance value

A total of 122 higher plant species, belonging to 108 genera and 55 families, were recorded in the study area. The tree layer comprised 54 species, with *Quercus variabilis* emerging as the absolute dominant species; its 1,693 individuals accounted for 88.82% of the total tree layer abundance. The shrub layer also contained 54 species, in which *Quercus variabilis* remained dominant, representing 22.37% of the total individuals.

The herb layer consisted of 74 species, with *Carex breviculmis* identified as the absolute dominant species, accounting for 17.16% of the total individuals. Two plant species under national Class II protection were discovered. *Emmenopterys henryi* is a rare and endangered tree species with important scientific and conservation value. *Cymbidium goeringii* is a well-known protected orchid. Their distribution is narrow and they are sensitive to human disturbance. Based on these data, the scientific names, quantities, protection levels, distribution plots, and vegetation layers for both invasive and protected species were integrated into the Table 2. Both invasive species identified are herbs; the counts for *Erigeron sumatrensis* and *Bidens pilosa* are consistent with their recorded abundances in the herb layer.

Although *Erigeron sumatrensis* and *Bidens pilosa* currently occur at low abundance and narrow distribution, both are listed as Level 1 aggressive invasive species with high seed production, strong wind-dispersal ability, and high tolerance to disturbed habitats. Under increasing human disturbance, they pose significant risks of rapid expansion. Therefore, long-term monitoring, timely manual removal, and strict control of anthropogenic disturbance are strongly recommended for early prevention and control. Among them, *Erigeron sumatrensis* is a common invasive herb belonging to the genus *Erigeron* in the Asteraceae family. Invasive plants *Erigeron sumatrensis* and *Bidens pilosa* have strong reproduction and dispersal abilities. They can occupy niches, reduce the growth of native herbs, decrease species richness, and affect community stability and ecosystem health.

Among the two recorded protected species, *Emmenopterys henryi* occurs as an associate species in the tree layer, while *Cymbidium goeringii* is a dominant associate species in the herb layer. Both are classified as National Class II protected wild plants, and their recorded counts align precisely with the individual records in their respective vegetation layers. *Cymbidium goeringii* was identified across five plots, indicating a relatively broad distribution within the study area and making it a key protected species within the herb layer. In contrast, *Emmenopterys henryi* was restricted to a single plot, suggesting that its habitat requires require priority conservation efforts.

Variations in the growth traits of primary species across the tree, shrub, and herb layers reflect distinct competitive advantages and niche characteristics within the community.

In the tree layer (Figure 3A), the average height, DBH, and crown width were 8.01 m, 9.08 cm, and 2.72 m, respectively. *Pinus massoniana* exhibited the greatest average height (15.62 m) and DBH (16.04 cm), while *Quercus variabilis* possessed the largest average crown width (4.28 m); the latter's average was notably increased by several large individuals with crown widths reaching 11.0–11.5 m.

In the shrub layer (Figure 3B), the primary species had an average height of 1.37 m, basal diameter of 1.39 cm, coverage of 11.40%, and cluster width of 0.86 m. Among these, *Cotinus coggygria* var. *cinereus* exhibited the highest average height (2.36 m) and cluster width (1.22 m), while *Quercus variabilis* possessed the largest average basal diameter (2.82 cm) and *Pistacia chinensis* attained the highest average coverage (15.88%).

In the herb layer (Figure 3C), the average height and coverage of main species were 14.92 cm and 14.43%, respectively. *Iris lactea* reached the maximum values for both height (20.67 cm) and coverage (45.58%), whereas the lowest values were observed in *Crepidiastrum lanceolatum* (1.83 cm in height) and *Cymbidium goeringii* (0.63% in coverage).

In the tree layer, *Quercus variabilis* exhibits the highest importance value (63.88%), far exceeding all other species and identifying it as the foundation species of the community. Its exceptionally high relative abundance (57.72%) indicates a large population with robust natural regeneration, while its comparatively lower relative dominance and relative height suggest that the forest is primarily composed of young and middle-aged individuals. Conversely, certain tree species occur at low densities but possess high relative height and dominance, representing scattered emergent trees; for

TABLE 2 Statistics of invasive and protected plant species in the study area.

Species category	Species name	Count	Invasion level	Plot ID
Invasive species	Erigeron sumatrensis	1	Level 1 (Aggressive Invasion)	3
	Bidens pilosa	4	Level 1 (Aggressive Invasion)	6
Protected species	Emmenopterys henryi	2	National Class II Protected Wild Plant	5
	Cymbidium goeringii	9	National Class II Protected Plant	1, 2, 3, 4, 11

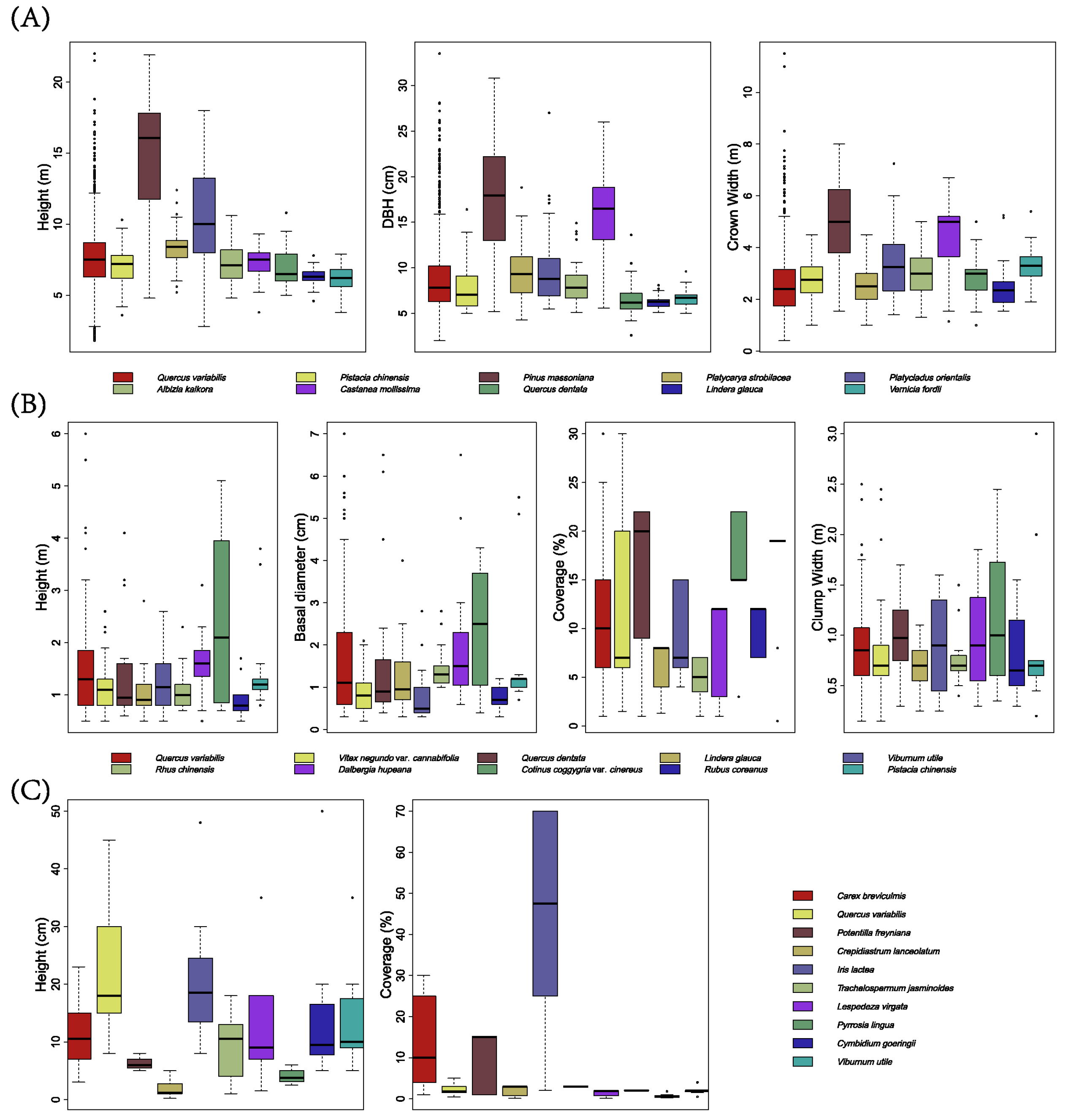


FIGURE 3
Growth traits of primary species across different canopy layers. **(A)** Tree height, diameter at breast height (DBH), and crown width of primary species in the tree layer; **(B)** plant height, basal diameter, coverage, and clump width of primary species in the shrub layer; **(C)** plant height and coverage of primary species in the herb layer.

instance, *Firmiana simplex* and *Quercus aliena* exhibited the highest relative dominance values at 5.83% and 5.35%, respectively. These species consist of few individuals with large diameters that occupy the upper canopy. In the shrub layer, *Quercus variabilis* also maintains the highest importance value (27.16%) and relative abundance (22.44%), confirming its role as the foundation species across the entire community. Meanwhile, *Celtis sinensis* recorded the highest relative dominance (12.40%) and relative height (4.41%) in the shrub layer. Despite its low abundance, the species' large individual stature made it a structural keystone of the community. In the herb layer, *Phragmites australis* holds the highest importance value (32.20%) and relative coverage (4.15%). Meanwhile, *Equisetum hyemale* and *Crataegus cuneata* exhibit the greatest relative abundance (18.35%) and relative height (4.15%), respectively (Figure 4).

3.2 Species diversity and community structure

Species diversity varied significantly across community layers, exhibiting a descending order of: shrub layer > herb layer > tree layer (Figure 5A). The tree layer exhibited generally low species

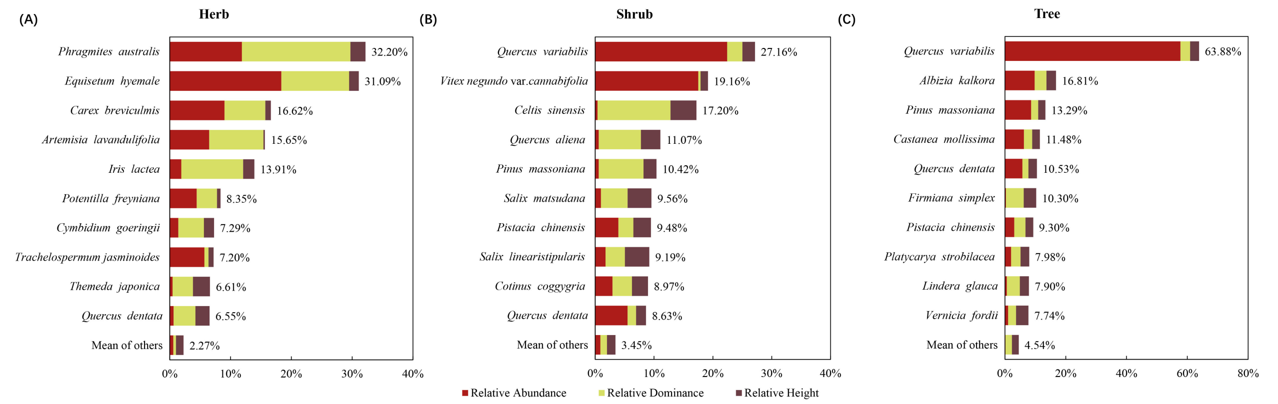


FIGURE 4
Importance values of dominant species in tree, shrub and herb layers. **(A)** Tree layer (top 12 species); **(B)** Shrub layer (top 12 species); **(C)** Herb layer (top 12 species). Species with low importance values were combined into "Others".

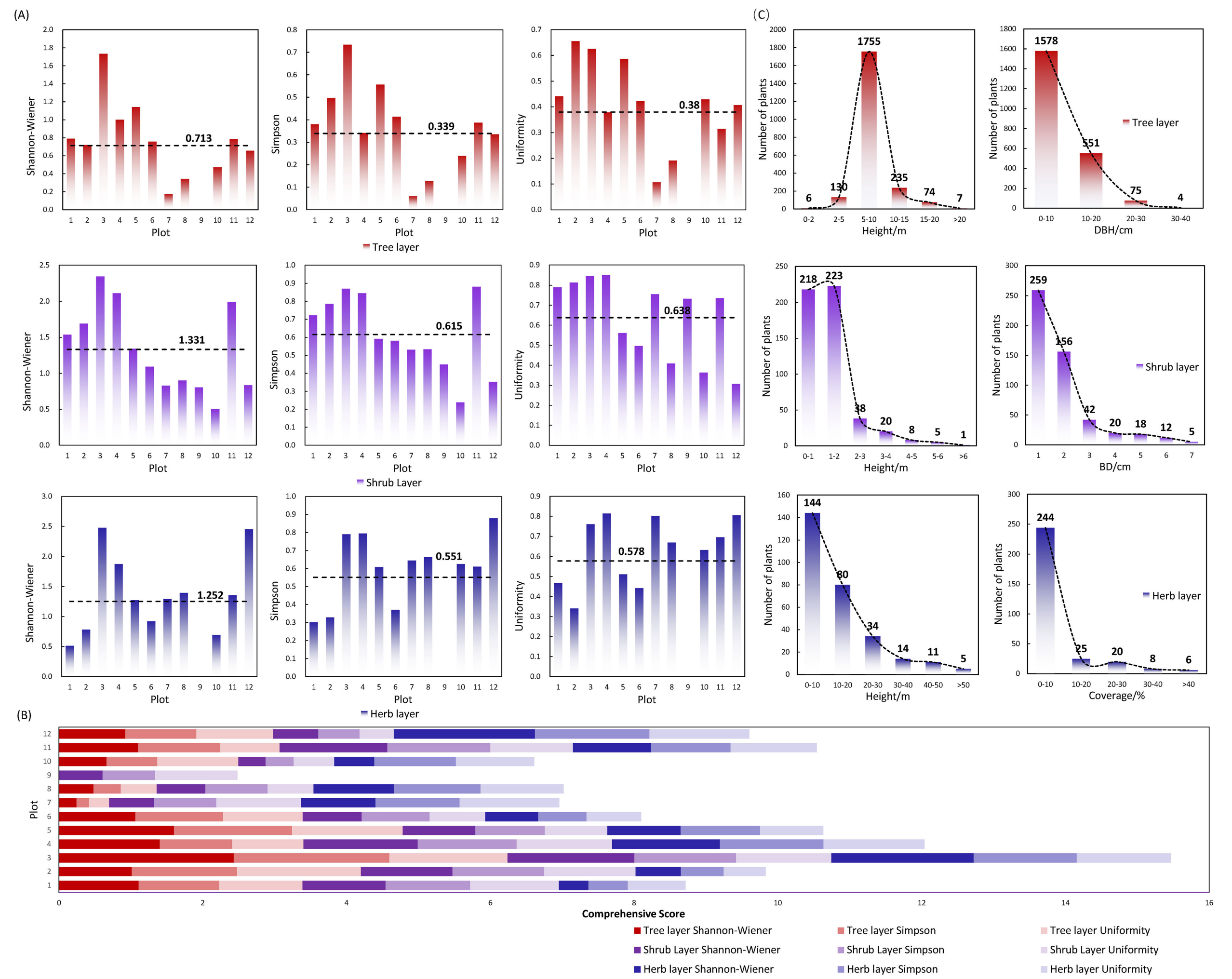


FIGURE 5
Analysis of species diversity and community structure. **(A)** Variation in Shannon-Wiener, Simpson, and Evenness indices across vertical layers; **(B)** Comprehensive diversity score and spatial pattern of 12 sample plots; **(C)** Schematic diagram of vertical community structure: tree layer, shrub layer, and herb layer.

diversity, with the Shannon-Wiener, Simpson, and Evenness indices recorded at 0.713, 0.339, and 0.38, respectively. The absence of trees in certain plots indicates an incomplete vertical structure and poor regeneration within this layer. In contrast, the shrub layer exhibited the highest diversity indices across all three layers, characterized by high species richness and a balanced distribution. With a Shannon-Wiener index of 1.331, a Simpson index of 0.615, and an Evenness index of 0.638, the shrub layer is the primary contributor to the community's overall species diversity. Diversity indices for the herb layer fluctuated significantly across plots, reflecting pronounced habitat heterogeneity.

The composite diversity index revealed pronounced spatial heterogeneity across the 12 plots, despite considerable fluctuations in individual indices at the plot level (Figure 5B). The range of the composite diversity index reached 12.99: Plot 3 attained the highest scFigureore (15.47), characterized by high index values across the tree, shrub, and herb layers. This signifies a complete vertical structure, balanced species distribution, and optimal developmental status. Conversely, Plot 9 recorded the lowest score (2.48); the absence of species in the tree and herb layers, coupled with a sparse shrub layer, demonstrates a severely truncated community structure. The remaining plots scored between 6.61 and 12.04 along a clear gradient: Plots 4, 5, and 11 exhibited above-average scores with relatively complete structures, while Plots 7, 8, and 10 ranked below average, characterized by low diversity and Imbalanced inter-layer species composition. Overall, while inter-layer differences for individual indices were minor, comprehensive developmental levels varied significantly among plots, reflecting pronounced spatial heterogeneity in habitat conditions and successional stages within the study area.

Based on growth traits, the community's vertical structure follows a distinct pattern (Figure 5C): the tree layer provides the primary structural dominance, followed by an intermediate shrub layer and a relatively sparse herb layer. This significant differentiation in structural attributes among layers is consistent with the development of secondary communities. The tree layer serves as the structural foundation of the community, with tree heights primarily concentrated between 5–10 m (accounting for 79.52% of individuals) and DBH dominated by small-diameter classes of 0–10 cm (71.46%). This indicates a forest dominated by young and middle-aged trees with a scarcity of large-diameter, tall individuals, suggesting the community is in a mid-successional stage. The shrub layer is characterized by heights in the 0–2 m range and basal diameters primarily within the 0–1 cm class; it is composed mostly of small shrubs and young clusters with very few tall or large-diameter individuals, reflecting limited structural development. Similarly, the herb layer is poorly developed, with heights mostly below 10 cm and coverage generally under 10%, indicating a short stature and low overall density within the ground cover.

3.3 Forest environmental quality analysis

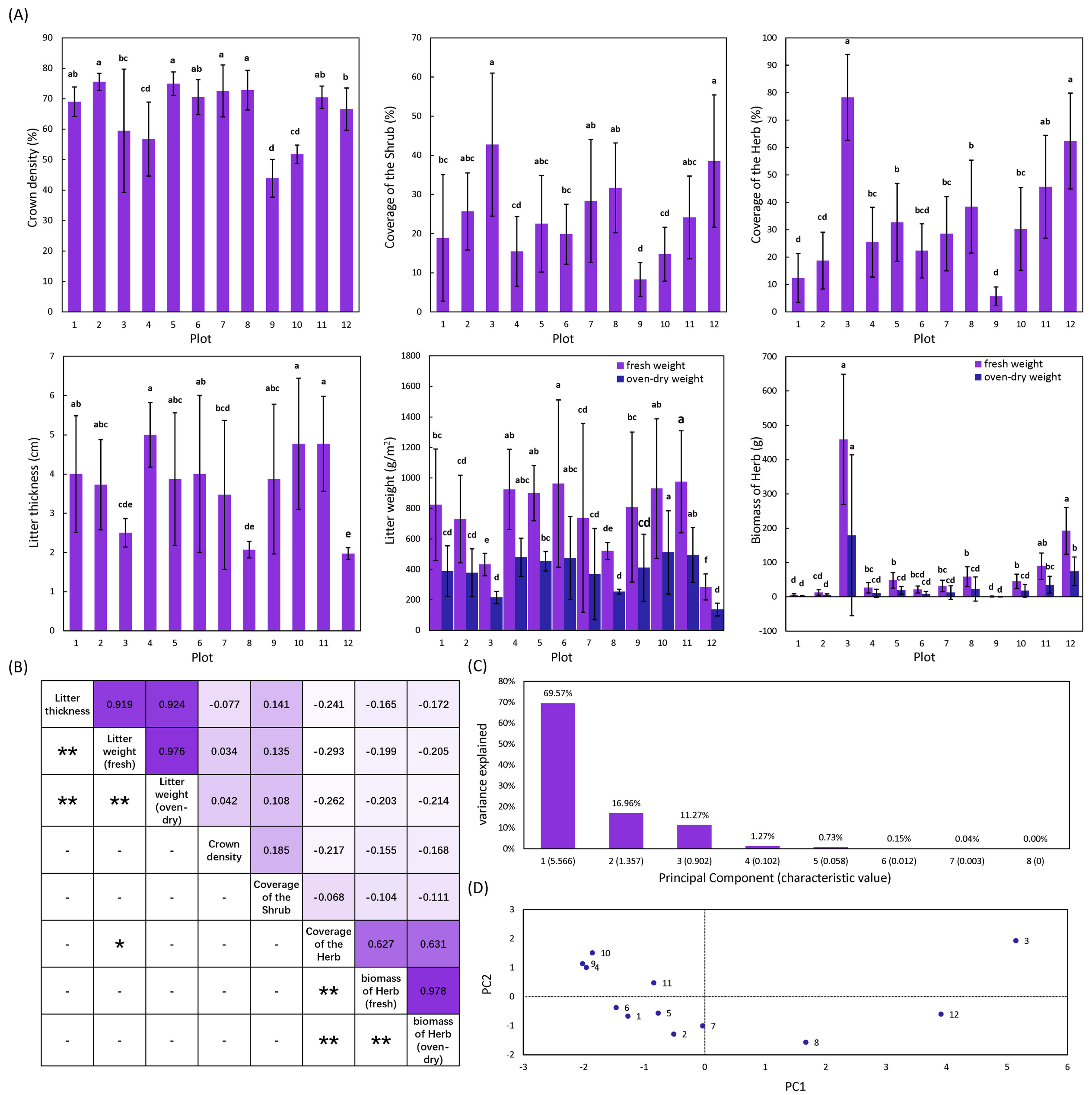
Statistical analysis revealed significant differences in litter, biomass, and community coverage indicators across the 12 plots ($P< 0.05$, Figure 6A). In summary, the dry and fresh weights of litter peaked in Plots 10 and 11, while reaching their minimum in Plot 12; correspondingly, litter thickness was greatest in Plot 4 and lowest in Plot 12. Canopy closure was generally high, with most plots ranging between 65% and 75%, except for Plot 9, which exhibited significantly lower density. Both shrub and herb coverage peaked in Plot 3 and reached their minimum in Plot 9, demonstrating a consistent spatial distribution pattern across the understory layers. Herb biomass (both dry and fresh weight) exhibited highly significant variation across plots; Plot 3 peaked with values substantially higher than all other plots, reflecting the most robust herb development in the study area. Collectively, Plot 3 exhibits the most favorable habitat conditions and the most well-developed understory, whereas Plots 9 and 12 are characterized by inferior ecological indicator and relatively simple community structures.

Correlation analysis (Figure 6B) revealed that litter thickness, fresh weight, and dry weight were all significantly positively correlated (r = 0.919–0.976), suggesting that any of these three indicators can serve as an effective proxy for litter accumulation. Herb coverage was significantly positively correlated with both fresh and dry biomass; furthermore, herb fresh weight was highly significantly positively correlated with dry weight (r = 0.978), indicating that biomass consistently represents herb growth status. Notably, litter fresh weight was significantly negatively correlated with herb coverage (r = -0.293). This suggests that that greater litter accumulation constrains herb coverage and biomass, illustrating the inhibitory effect of the litter layer on herb growth. Canopy closure showed no significant correlation with litter, shrubs, or herbs, suggesting it does not exert a limiting influence on surface-layer characteristics in this region. Similarly, shrub coverage was independent of litter, trees, and herbs indicators, with no significant correlations observed.

Principal component analysis (PCA) revealed that the first three principal components explained 97.80% of the total variance, with PC1 and PC2 accounting for 69.57% and 16.96%, respectively (Figure 6C). PC1 was mainly loaded by herb coverage, herb dry biomass, and shrub coverage, representing understory vegetation development. PC2 was mainly loaded by litter thickness, litter fresh weight, and litter dry weight, representing litter accumulation. Their cumulative explained variance of 86.53% was sufficient to capture the primary differences across the sites. The ordination plot based on PC1 and PC2 (Figure 6D) clustered the 12 plots into two distinct groups: a group on the left (PC1< 0) containing Plots 1, 2, 4, 5, 6, 7, 9, 10, and 11, and a group on the right (PC1 > 0) consisting of Plots 3, 8, and 12.Plot 3 exhibited the most pronounced differentiation, positioned at the far right of the PC1 axis with a high PC2 value. Plots 4, 9, and 10 were tightly clustered on the left, reflecting similar community structures and habitat characteristics, while Plots 8 and 12 formed a distinct secondary cluster in the lower-right region. Overall, the PCA ordination clearly elucidated habitat heterogeneity and community differentiation patterns among the sample plots in the study area.

4 Discussion

This study conducted a comprehensive field investigation in the intake area of the Middle Route of the SNWDP. We analyzed species



Litter thickness	0.919	0.924	-0.077	0.141	-0.241	-0.165	-0.172
**	Litter weight (fresh)	0.976	0.034	0.135	-0.293	-0.199	-0.205
**	**	Litter weight (oven-dry)	0.042	0.108	-0.262	-0.203	-0.214
-	-	-	Crown density	0.185	-0.217	-0.155	-0.168
-	-	-	-	Coverage of the Shrub	-0.068	-0.104	-0.111
-	*	-	-	-	Coverage of the Herb	0.627	0.631
-	-	-	-	-	**	biomass of Herb (fresh)	0.978
-	-	-	-	-	**	**	biomass of Herb (oven-dry)

FIGURE 6
Analysis of forest environmental quality across different sample plots. **(A)** Variation in litter thickness, coverage, and herb biomass indicators across 12 sample plots; **(B)** Pearson correlation coefficients among litter, coverage, and biomass indicators; **(C)** Variance explained by the first five principal components; **(D)** Principal coordinate ordination of 12 sample plots based on PC1 and PC2. The asterisk * indicates a significant difference at P < 0.05, and double asterisks ** represent an extremely significant difference at P < 0.01. The lowercase letters denote significant differences at the P < 0.05 level based on multiple comparison analysis.

composition, plant diversity, community structure, dominant species, protected plants, and invasive plants. The objectives were to reveal the ecological characteristics of regional forests, identify key conservation targets, and fill data gaps for evidence-based management. The findings provide a scientific basis for forest conservation, ecological restoration, and biodiversity maintenance in strategic water-source areas and support the long-term safe operation of the SNWDP (Yubin, 2025).

Two national Class II protected wild plants *Emmenopterys henryi* and *Cymbidium goeringii* show disparate spatial distribution in this region. *E. henryi* only appears in a single plot with narrow surviving habitat, while *C. goeringii* distributes across five sample plots with stronger adaptability. Strict *in-situ* protection should be implemented: human disturbance is restricted around the habitat of *E. henryi*, and regular population monitoring is carried out to prevent illegal digging of wild *C. goeringii*.

Erigeron sumatrensis and *Bidens pilosa* are widespread invasive herbs across most prefecture-level cities of Henan according to previous surveys. Their present abundance stays low in Nanyang

City water source zone compared with plain regions in northern and eastern Henan, but strong reproductive and spread capacity creates high invasion risk under frequent human interference. Regular monitoring and manual removal are necessary to control future population expansion.

The species diversity of the surveyed communities showed a consistent layer pattern of shrub layer > herb layer > tree layer. This vertical diversity distribution is a typical characteristic of secondary forests in transitional climate mountain areas. The relatively low diversity of the tree layer is mainly attributed to long-term human disturbance and historical vegetation logging in the study area, which limits the regeneration and community stability of arbor species.

5 Conclusion

This study systematically investigated plant diversity and community characteristics in the canal intake area of the Middle Route of the SNWDP. These findings fill key data gaps for vegetation assessment in the highly sensitive intake zone and provide direct scientific support for forest conservation, biodiversity maintenance and ecological restoration. Maintaining community stability and plant diversity is essential for sustaining water conservation, purification, and carbon sequestration functions, which are critical to the ecological security and long–term stable operation of the SNWDP.

Based on the results, three targeted management strategies are proposed: first, strict in–situ conservation for *Emmenopterys henryi* and *Cymbidium goeringii* with restricted human disturbance; second, moderate stand tending to promote the development of large–diameter trees and improve vertical structure; third, regular monitoring and control of invasive plants to prevent further spread.

This study enhances the scientific basis for water–conservation forest protection in strategic water–source areas and provides a reference for ecological conservation and restoration under similar engineering contexts worldwide.

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

XL: Conceptualization, Data curation, Resources, Writing – original draft. YW: Formal analysis, Funding acquisition, Writing – original draft. YK: Investigation, Writing – review & editing. WW: Methodology, Writing – review & editing. CZ: Software, Writing – original draft. CW: Validation, Writing – original draft. MW: Visualization, Writing – review & editing. PY: Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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Supplementary material

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