CHARACTERISTICS AND DRIVING FACTORS OF UNDERSTORY HERBACEOUS COMMUNITIES IN DIFFERENT PLANTATIONS AT PLAIN AFFORESTATION IN BEIJING

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Abstract. This study examined understory herb diversity and soil drivers in six Beijing Plain plantations: *Styphnolobium japonicum* (*Stj*), *Robinia pseudoacacia* (*Rop*), *Fraxinus chinensis (Frc)*, *Acer truncatum (Act)*, *Ulmus pumila* 'Jinye' (*Ulp*), and *Salix matsudana* (*Sam*). Key findings: (1) 34 herb species were identified, predominantly the family *Asteraceae* (41.18%), with *Cirsium setosum*, *Artemisia argyi*, *Digitaria sanguinalis*, and *Artemisia scoparia* as dominant species. (2) *Rop* plantations showed significantly higher Margalef, Simpson, Shannon-Wiener, and Pielou indices than others. (3) Soil properties varied significantly among plantations, with available nitrogen (AN, 17.27%), soil organic carbon (SOC, 16.81%), bulk density (BD, 10.92%), soil water content (SWC, 8.51%), and non-capillary porosity (NCP, 8.19%) being key factors affecting herb importance values. (4) Structural equation modeling revealed stand structure (path coefficient = 0.550) as the primary driver of diversity indices, outweighing stand density and soil characteristics. The results highlight *Rop* plantations' ecological advantages and demonstrate how soil chemistry and forest structure jointly shape herb communities. This research provides critical baseline data for optimizing plantation management and ecological restoration strategies in northern China's urban forest ecosystems.
Keywords: *plantation, understory herb, stand structure, redundancy analysis, PlS-SEM*

Introduction

Species diversity, functioning as a fundamental characteristic of plant communities, not only quantifies biodiversity at the taxonomic level but also operates as a principal driver of ecosystem multifunctionality and stability (Fu et al., 2004; Cui et al., 2022). Species diversity enhances ecosystem resilience and mitigates the impacts resulting of biotic and abiotic disturbances (Hu et al., 2025). In plantation ecosystems characterized by simplified stand structures, plant diversity is principally manifested through understory vegetation components, with particular emphasis on the herbaceous stratum (Gilliam et al., 2007). Understory herb diversity plays an important role in improving soil nutrient cycling, facilitating community energy flow, and promoting the regeneration and development of community structure (Harianja et al., 2024). Landuyt et al. (2019) reported that the nutrient concentrations in the understory plants were1.5 to 5 times higher than those in overstorey leaves; Xu et al. (2020) demonstrated that understory herbaceous plants exhibit high functional diversity, thereby playing a crucial role in niche complementarity and efficient resource utilization; Thrippleton et al. (2018) indicated that understory herbs can affect the regeneration of woody seedlings. Therefore, studying the species diversity of understory herbaceous plants and their influencing factors is helpful for us to thoroughly understand species coexistence and maintenance mechanisms.

Numerous factors influence understory herbaceous species diversity, and identifying the key driving factors has emerged as a major challenge in forest ecology research. Previous studies have shown that stand density (Ali et al., 2019; Zhang et al., 2019; Deng et al., 2023), stand structure (Cook et al., 2015; Rawlik et al., 2018; Tinya et al., 2021) and soil factors (Fu et al., 2004; Wasie et al., 2020; Wu et al., 2022) can affect the diversity of understory herbs, yet the conclusions have been inconsistent. For instance, Rago et al.'s (2021) research on Pinus ponderosa plantations in Patagonia revealed a negative correlation between understory herbaceous diversity and both diameter at breast height (DBH) and tree height; Zhang et al. (2022) showed that there was no correlation observed between the DBH and the understory herbaceous diversity in Platycladus orientalis plantations located in the mountainous region of Beijing; While, the study of Guo et al. (2022) on the integration analysis of Chinese plantation found a positive correlation between them. The conclusions regarding the impact of soil factors on understory herb diversity are also varied. Geng et al. (2024) showed that SWC and SOC were the primary driving factors of understory herbaceous species diversity in biodiversity hotspots in Southwest China. However, Xu et al. (2016) found no significant correlation between understory herb species diversity and SWC or SOC, but identified pH and AP as the main driving factors for understory herb species diversity in tropical seasonal rainforests. In conclusion, the mechanism that affects understory herbaceous diversity is complex. When considering only the influence of a single factor on understory herbaceous diversity and neglecting the interactions between different factors, the coupling mechanism that governs understory herbaceous species diversity cannot be accurately revealed.

At present, there are few studies on the characteristics of understory herbaceous communities in Beijing plain area, and even fewer have focused on the driving factors of understory herbaceous diversity based on stand structure, stand density, and soil properties. In 2012 and 2018, Beijing municipal government successively launched the "One Million-Mu (666 km^2) Plain Afforestation Project," resulting in the establishment of a large area of urban plantations in the Beijing plain area (Zhao et al., 2024). By 2023, Beijing's urban forest coverage had reached 44.9%, with over 70 million trees planted (Yao et al., 2019; Pan, 2024), significantly impacting the urban ecosystem. To ensure the maximum ecological benefits, maintain the stability of community structure, and achieve real forest structure and function, it is urgent to explore the characteristics, diversity, and driving factors of understory herbaceous communities in Beijing Plain area. In this paper, we selected six common types of plantations in Beijing Plain area for study, including *Styphnolobium japonicum* (*Stj*), *Robinia pseudoacacia* (*Rop*), *Fraxinus chinensis (Frc)*, *Acer truncatum (Act)*, *Ulmus pumila* 'Jinye' (*Ulp*), and *Salix matsudana* (*Sam*). We investigated the stand information and understory herbaceous vegetation of these

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plantations, collected soil samples to determine physicochemical properties, and used PLS-SEM to scientifically characterize understory herbaceous diversity and explore the mechanisms underlying the driving factors affecting it. The aims of this research are to: (1) clarify characteristics of stand and understory herbaceous communities in different plantations; (2) compare the difference in understory herb diversity and soil physicochemical properties among various plantations; (3) explore the key soil and stand driving factors affecting the diversity of understory herbaceous plants in Beijing Plain area. In conclusion, this study holds significant importance for maintaining ecological balance, promoting ecological restoration, and improving ecological environment in Beijing Plain area. Furthermore, it can provide a theoretical basis for afforestation practices and the management of urban plantations in this region.

Materials and methods

Study area

The study site was situated in Fangshan District of Beijing, within the geographical coordinates of 115°25′ to 116°15′ East and 39°30′ to 39°55′ North (*Fig. 1*). The primary vegetation covering this area consists of deciduous broad-leaved forests. The average temperature and annual precipitation in the plain area of Fangshan District are 13.2°C and 670.4 mm, respectively. Vegetation in Fangshan District mainly consists of warm-temperate deciduous broad-leaved forest. The study area is classified as part of the North China region within the Sino-Japan Forest Subkingdom based on the floristic regionalization of China. Since 2018, a total of 133,600 mu (89.33 km^2) plantation has been completed in the second “One Million-Mu Plain Afforestation Project” in Fangshan District. By 2024, the forest coverage rate of the whole district reached 38.24%. The main afforestation tree species in the area are deciduous trees, such as *Rop*, *Frc*, *Sam*, *Stj*, *Act* and *Ulp* etc.

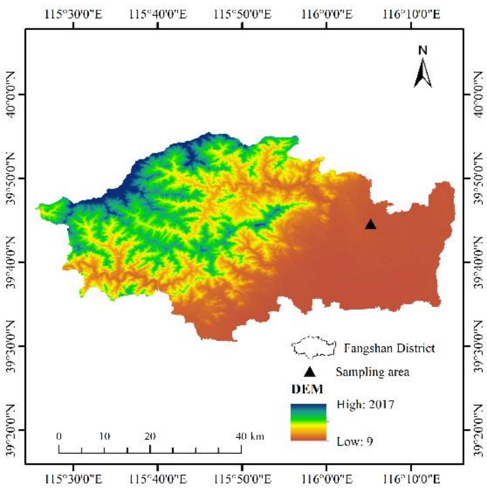

Figure 1. *Location map of the study area*

Sample plot setting and community investigation

Through comprehensive survey of afforestation in Fangshan District from June to August 2021, we selected 6 typical plantation plots, including *Rop*, *Stj*, *Frc*, *Act*, *Ulp* and *Sam*. For each plantation type, three 20*20 m quadrats were systematically selected

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within the study area to represent the variability and conditions of each plantation type. Within each tree quadrat, we further set up three 1 m × 1 m herbaceous quadrats for investigation. To characterize forest structure, counted the number of trees within the tree quadrats. We measured the diameter at breast height (DBH), tree height and crown length of every tree. 3-5 replicate measurements were conducted for each parameter, and the mean was calculated. The DBH was measured using a diameter tape to determine the diameter of the tree trunk at a height of 1.3 meters above the ground. The crown width was assessed by measuring the lengths of the tree crown in the east-west and north-south directions using a measuring tape. Tree height was measured using the pole method. For the herbaceous quadrats, we identified the herbaceous species and recorded their height, coverage, and number. To characterize the study areas, detailed baseline information for different plantations is provided in *Table 1*.

Table 1. *Basic characteristics of the different plantations*

Type	Family	Genus	DBH (cm)	Tree height (m)	Crown length (m)	Density (stem·ha^{-1})
Stj	*Fabaceae*	*Styphnolobium*	8.26 ± 0.21c	6.33 ± 0.21c	3.60 ± 0.18b	366.67 ± 22.05d
Rop	*Fabaceae*	*Robinia*	9.54 ± 0.15b	8.10 ± 0.17a	4.97 ± 0.12a	750.00 ± 14.43b
Frc	*Oleaceae*	*Fraxinus*	9.09 ± 0.13b	6.79 ± 0.10c	2.72 ± 0.07c	1008.33 ± 22.05a
Act	*Sapindaceae*	*Acer*	6.48 ± 0.11d	5.27 ± 0.06d	2.53 ± 0.11c	575.00 ± 14.43c
Ulp	*Ulmaceae*	*Ulmus*	8.11 ± 0.47c	4.13 ± 0.32e	2.69 ± 0.28c	1041.67 ± 8.33a
Sam	*Salicaceae*	*Salix*	12.58 ± 0.52a	7.40 ± 0.33b	3.72 ± 0.29b	583.33 ± 16.67c

Different lowercase letters indicate significant differences among different plantations ($p < 0.05$)

Soil samples from all plantation plots were collected using protocols analogous to those described in our prior investigation (see Qiang et al., 2024 for details). Soil physical indicators, including SWC, BD, capillary porosity (CP), and NCP, were determined following the protocols outlined in Reference (ISSAS, CAS, 1978). The main soil chemical indicators included SOC, total nitrogen (TN), total phosphorus (TP) and AN, available phosphorus (AP), available potassium (AK) and pH. The measurement methods for these chemical indicators are as follows (Bao, 2000).

Calculation methods of diversity correlation index data analysis

We calculated the importance value and species diversity correlation index of understory herbs in the sample plots, and the calculation formulas are shown in *Table 2* (Zhang et al., 2011).

RDA and PLS-PM method

Prior to conducting RDA, we performed a Detrended Correspondence Analysis (DCA) to assess the gradient length of the herbaceous species data. The gradient length was determined to be 1.93, indicating that the RDA method was suitable for analysis. To ensure the validity of the RDA results, we evaluated multicollinearity among the soil environmental variables using Variance Inflation Factors (VIFs). All VIF values were below the recommended threshold of 10, indicating that multicollinearity was not a significant concern in this analysis.

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Table 2. *Indicator definition and formula*

Variable	Formula	Define
Importance value (P_i)	$P_i = (RD + RH + RC) / 3$	RD, RH and RC are the ratio of the density, height and coverage of the ith species to the overall density, height and coverage of species
Margalef index (M)	$M = (S-1) / \ln N$	S is the number of species; N is the total number of individuals of all species
Simpson index (D)	$D = 1-\sum_{i=1}^{s} P_i^2$	
Shannon-Wiener index (H)	$H = -\sum_{i=1}^{s} P_i \ln P_i$	
Pielou index (J_{sw})	$J_{sw} = \frac{H}{\ln S}$	

In PLS-SEM methodology, latent variables are operationalized by the measurement model, while interconstruct relationships are examined through the structural model (Hair et al., 2012; Sarstedt et al., 2016). The formal equations governing these analytical components are documented in *Table 3*. Prior to conducting the PLS - SEM analysis, we assessed collinearity between indicators using VIFs. To ensure the validity of the model, we verified convergent and discriminant validity. Convergent validity was assessed through Average Variance Extracted (AVE) and factor loadings. Discriminant validity was verified using the Heterotrait-Monotrait (HTMT) ratio. We evaluated the predictive ability of the model using the Stone-Geisser Q^2 index.

Table 3. *Indicator definition and formula of PLS-SEM*

<table>
<tr><th>Formula</th><th colspan="5">Define</th></tr>
<tr><td rowspan="2">$x = \Lambda x\xi + \delta$</td><td>x</td><td colspan="2">Λx</td><td colspan="2">δ</td></tr>
<tr><td>Exogenous indicators</td><td colspan="2">The matrix of factor loadings of ξ to x</td><td colspan="2">The measurement error</td></tr>
<tr><td rowspan="2">$y = \Lambda y\eta + \varepsilon$</td><td>y</td><td colspan="2">Λy</td><td colspan="2">ε</td></tr>
<tr><td>Endogenous indicators</td><td colspan="2">The matrix of factor loadings of η to y.</td><td colspan="2">The measurement error</td></tr>
<tr><td rowspan="2">$\eta = B\eta + \Gamma\xi + \zeta$</td><td>η</td><td>ξ</td><td>B</td><td>Γ</td><td>ζ</td></tr>
<tr><td>The endogenous latent variable</td><td>The exogenous latent variable</td><td>The regression path coefficient of the effect between different η</td><td>The effect of ξ on η</td><td>Regression residual</td></tr>
</table>

Statistical analysis

Excel2010 was used for data processing and calculation. SPSS26.0 was used for one-way ANOVA. We employed Tukey's Honestly Significant Difference test (Tukey HSD) for post hoc testing. RDA analysis and mapping were performed in R 4.3.3, using the "vegan" package (Dixon, 2003). SmartPLS 4 was used for PLS-SEM to analyze the driving factors of herbaceous diversity and to map the driving factors.

Results

Characteristics of understory herbaceous community

There were 34 species of understory herbs in the study area, belonging to 15 families and 30 genera. *Asteraceae* were the most prevalent family, accounting for 41.18%. The

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order of understory herb species in the 6 plantations was *Rop* (18) > *Stj* (16) = *Sam* (16) > *Act* (14) > *Ulp* (13) > *Frc* (10). The dominant species of understory herbs are *Cirsium setosum*, *Artemisia argyi*, *Digitaria sanguinalis* and *Artemisia scoparia* (*Table 4*).

Table 4. *The main plant species and importance values in different plantations*

Type	Total number of plant species	Top five importance values				
Stj	16	*Cirsium setosum*	*Digitaria sanguinalis*	*Cnidium monnieri*	*Erigeron canadensis*	*Lactuca indica*
		0.2484	0.2157	0.1080	0.0979	0.0642
Rop	18	*Artemisia argyi*	*Humulus scandens*	*Cirsium setosum*	*Erigeron canadensis*	*Setaria viridis*
		0.1395	0.1320	0.0948	0.0839	0.0713
Frc	10	*Digitaria sanguinalis*	*Cirsium setosum*	*Artemisia scoparia*	*Chemopodium glaucum*	*Artemisia caruifolia*
		0.2532	0.1879	0.1870	0.0925	0.0873
Act	14	*Artemisia scoparia*	*Artemisia caruifolia*	*Digitaria sanguinalis*	*Setaria viridis*	*Artemisia argyi*
		0.2974	0.1351	0.1040	0.0807	0.0782
Ulp	13	*Digitaria sanguinalis*	*Cirsium setosum*	*Artemisia scoparia*	*Artemisia caruifolia*	*Setaria viridis*
		0.3177	0.1535	0.1295	0.1029	0.0713
Sam	16	*Digitaria sanguinalis*	*Artemisia scoparia*	*Erigeron canadensis*	*Setaria viridis*	*Plantago asiatica*
		0.2918	0.1181	0.0861	0.0824	0.0659

There were significant differences in the diversity of understory herbaceous species among different plantations (*Table 5*). Specifically, the values of M (3.88), D(0.92), H(2.66) and Jsw (0.92) for *Rop* were significantly higher than those of the other plantations. In contrast, *Frc* exhibited lower values of M (1.65) and H (2.01) compared to the other plantations, and this difference was statistically significant. Among the six plantations, *Ulp* had the lowest value of D (0.83), which was also statistically significant. As for *Stj*, its Jsw (0.81) was significantly lower than that of the other plantations, except for *Ulp*, which had a similar value of 0.82.

Table 5. *Diversity index of understory herbaceous species in different plantations*

Type	Margalef index (M)	Simpson index (D)	Shannon-Wiener index (H)	Pielou index (J_{sw})
Stj	2.87 ± 0.03b	0.86 ± 0.01b	2.26 ± 0.02c	0.81 ± 0.01c
Rop	3.88 ± 0.02a	0.92 ± 0.01a	2.66 ± 0.01a	0.92 ± 0.01a
Frc	1.65 ± 0.01f	0.84 ± 0.01c	2.01 ± 0.01f	0.87 ± 0.01b
Act	2.25 ± 0.19e	0.86 ± 0.01b	2.23 ± 0.01d	0.87 ± 0.02b
Ulp	2.33 ± 0.01d	0.83 ± 0.01d	2.11 ± 0.02e	0.82 ± 0.02c
Sam	2.67 ± 0.04c	0.86 ± 0.01b	2.38 ± 0.02b	0.86 ± 0.01b

Different lowercase letters indicate significant differences among different plantations ($p < 0.05$)

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Characteristics of soil physicochemical properties

As shown in *Table 6,* significant differences were found in soil physical characteristics. The SWC of Sam (22.91%) and *Act* (22.19%) was significantly higher than that of *Stj* (19.02%) and *Frc* (19.37%), whereas no significant difference was found between *Rop* (21.58%) and *Ulp* (21.42%). *Act* had a higher CP (36.67%) and a lower BD (1.50 g·cm^{-3}) compared to the other five plantations, with a significant difference in BD. For NCP, *Stj* (0.82%) had the lowest value and showed a significant difference from other plantations except for *Frc* (1.30%).

In terms of chemical characteristics, there were also differences among different plantations except for soil total nitrogen (TN) and pH. The soils of all the six plantations were weakly alkaline. The SOC (10.11 g·kg^{-1}) of *Ulp* was significantly higher than that of *Stj* (5.91 g·kg^{-1}), Act (5.69 g·kg^{-1}) and *Sam* (6.20 g·kg^{-1}). *Rop* had the largest TP and AK among the six plantations, which were 0.12 g·kg^{-1} and 91.18 mg·kg^{-1} respectively. The AP of *Sam* (15.60 mg·kg^{-1}) was significantly higher than that of *Stj* (9.33 mg·kg^{-1}), but it did not differ significantly from that of other plantations. The AN of *Act* (55.57 mg·kg^{-1}) was significantly higher than the others. With regard to soil depth, the chemical characteristics of the soil, except for TP and pH, decreased gradually, and the differences among soil layers were significant. However, there were no significant differences in soil physical characteristics among different soil layers.

Table 6. *Soil physicochemical characteristics of different plantations*

Type	SOC (g·kg^{-1})	TN (g·kg^{-1})	TP (g·kg^{-1})	AP (mg·kg^{-1})	AK (mg·kg^{-1})	AN (mg·kg^{-1})	pH	SWC (%)	BD (g·cm^{-3})	CP (%)	NCP (%)
Stj	5.91± 0.97b	0.32± 0.08a	0.11± 0.01ab	9.33± 1.56b	80.05± 9.56ab	40.64± 6.81b	7.55± 0.02a	19.02± 1.62c	1.60± 0.02a	32.34± 2.43c	0.82± 0.16b
Rop	7.97± 0.79ab	0.53± 0.08a	0.12± 0.03a	13.77± 2.34ab	91.18± 4.27a	39.11± 2.80b	7.55± 0.03a	21.58± 0.49ab	1.58± 0.02a	34.91± 0.53abc	1.72± 0.16a
Frc	8.33± 1.22ab	0.43± 0.11a	0.09± 0.02ab	11.38± 1.02ab	90.57± 6.84a	30.99± 4.01b	7.54± 0.02a	19.37± 0.66c	1.64± 0.03a	33.01± 0.60bc	1.30± 0.12ab
Act	5.69± 0.83b	0.56± 0.07a	0.06± 0.01b	13.59± 2.22ab	83.38± 5.41ab	55.57± 5.49a	7.55± 0.02a	22.19± 0.34a	1.50± 0.02b	36.67± 0.36a	1.72± 0.20a
Ulp	10.11± 0.93a	0.54± 0.07a	0.09± 0.02ab	12.00± 1.77ab	64.77± 4.62b	27.71± 1.34b	7.55± 0.02a	21.42± 0.50ab	1.58± 0.01a	34.64± 0.64abc	1.73± 0.29a
Sam	6.20± 1.03b	0.53± 0.08a	0.07± 0.01ab	15.60± 2.04a	78.23± 4.07ab	36.97± 3.25b	7.56± 0.02a	22.91± 0.92a	1.57± 0.02a	36.26± 0.83ab	1.75± 0.09a

Different lowercase letters indicate significant differences among different plantations ($p < 0.05$)

RDA of species distribution in understory herbaceous communities of different plantations

Based on the one-way ANOVA analysis of soil factors, significant differences were observed among all soil factors, with the exception of TN and pH. Consequently, we utilized RDA to evaluate the relationship between the importance value of understory herbaceous species and all soil physicochemical properties, excluding TN and pH. *Figure 2a* illustrates that the eigenvalues on the RDA1 and RDA2 axes contributed 35.66% and 29.41%, respectively. The cumulative contribution rates of eigenvalues was 65.07%, indicating that the RDA1 and RDA2 axes played a major role in explaining the composition and distribution of understory herbaceous species. Monte Carlo test analysis showed that SOC、AN、SWC、BD and NCP had a great impact on the

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importance value of understory herbs (*Fig. 2b*). The explanatory variations were ranked as follows: AN(17.27%) > SOC(16.81%) > BD(10.92%) > SWC(8.51%) > NCP(8.19%).

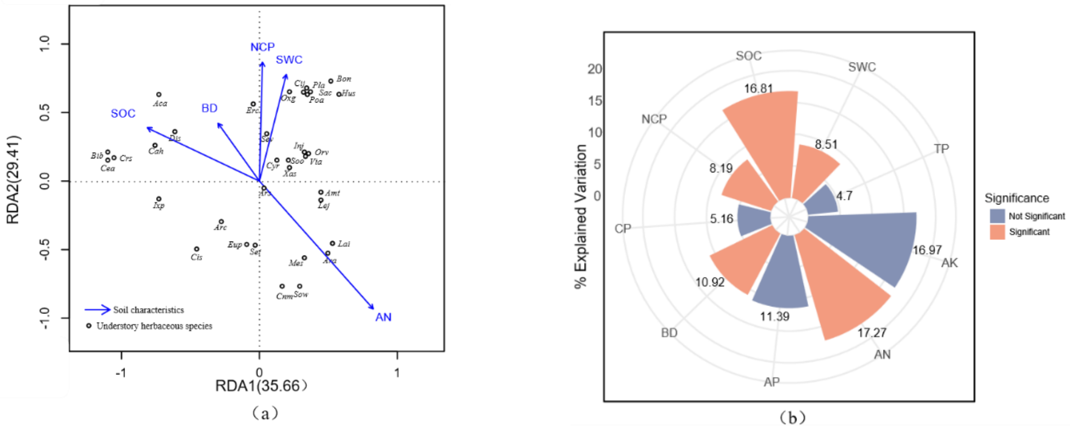

Figure 2. *(a) RDA analysis of importance values of understory herbs and soil characteristics. (b) Explanation variation of soil factors to the importance value of understory herbaceous species. Aca: Acalypha australis, Amt: Amaranthus tricolor, Ara: Artemisia argyi, Arc: Artemisia caruifolia, Ars: Artemisia scoparia, Bib: Bidens bipinnata, Bon: Boehmeria nivea, Cah: Calystegia hederacea, Cea: Centella asiatica, Cij: Cirsium japonicum, Cis: Cirsium setosum, Cnm: Cnidium monnieri, Crs: Crepidiastrum sonchifolium, Cyr: Cynanchum rostellatum, Dis: Digitaria sanguinalis, Erc: Erigeron canadensis, Eup: Euphorbia pekinensis, Hus: Humulus scandens, Inj: Inula japonica, Ixp: Ixeris polycephala, Lai: Lactuca indica, Lej: Leonurus japonicus, Mes: Melilotus suaveolens, Orv: Orychophragmus violaceus, Oxg: Oxybasis glauca, Pla: Plantago asiatica, Poa: Poa annua, Sac: Salsola collina, Set: Senna tora, Sev: Setaria viridis, Soo: Sonchus oleraceus, Sow: Sonchus wightianus, Via: Viola arcuate, Xas: Xanthium strumarium*

Analysis of driving factors of understory herbaceous species diversity under different plantations

To illustrate the relationship between species diversity and soil physicochemical factors, stand structure and stand density among different plantations, a Partial Least Squares Structural Equation Modeling (PLS-SEM) was constructed (*Fig. 3*). Stand structure (crown length, tree height and DBH), stand density, soil chemical characteristics (AN) and soil physical characteristics (BD) were the main factors contributing to changes in species diversity among different plantations. The results of the VIF test, the reliability and validity of the model, and the loadings for each of the manifest factors had an excellent fit for the requirements of fit reference values and the degree of adaptation (*Table 7*). In the PLS-SEM, the path coefficients of species diversity with different stand structures, stand density, soil chemical characteristics and soil physical characteristics were 0.550, −0.072, 0.085 and −0.058, respectively. We calculated the Stone-Geisser Q^2 values for all endogenous constructs using the blindfolding procedure. All values greater than 0 confirm the model’s predictive relevance. To rigorously assess discriminant validity, we added HTMT ratios. All values are below the conservative threshold of 0.85, demonstrating distinctness between constructs (*Table 8*).

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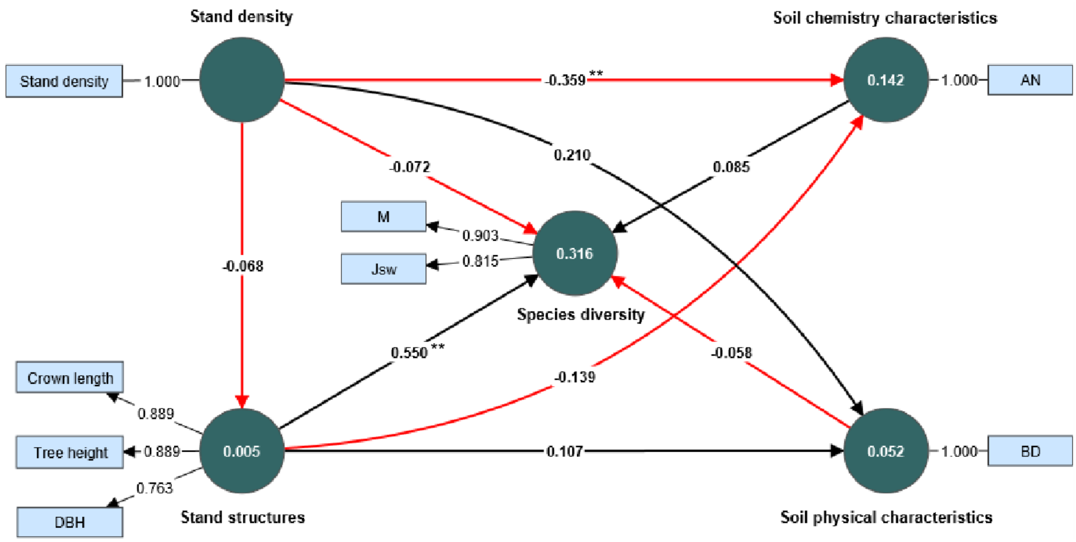

Figure 3. *Partial least squares structural equation modeling (PLS-SEM) analysis and validity of the effects of chemical characteristics, physical characteristics and stand structures on the species diversity. Red arrows indicate negative effects and black arrows represent positive effects. Numbers adjacent to arrows are the standard path coefficients.* $^{**}p < 0.01$

Table 7. *Assessing PLS-SEM models: variance inflation factor (VIF) analysis of each indicator and reliability and validity evaluations*

Driving factors	Indicators	Variance inflation factor (VIF)		Outer loadings		Composite reliability		Average variance extracted (AVE)		Q^2
		Reference value	Statistical value	Reference value	Statistical value	Reference value	Statistical value	Reference value	Statistical value	
Stand structure	Crown length	1<VIF<3	1.73	>0.7	0.89	>0.6	0.88	>0.5	0.72	0.40
	Tree height		2.24		0.89					0.52
	DBH		1.76		0.76					0.38
Stand density	Stand density		1.00		1.00		/		/	1.00
Soil chemistry characteristics	AN		1.00		1.00		/		/	1.00
Soil physical characteristics	BD		1.00		1.00		/		/	1.00
Species diversity	J_{sw}		1.31		0.82		0.70		0.74	0.23
	M		1.31		0.90					0.24

Table 8. *Modeling PLS-SEM of the heterotrait-monotrait ratio (HTMT) of each indicator*

		HTMT
Soil physical characteristics	Soil chemistry characteristics	0.28
Species diversity	Soil chemistry characteristics	0.07
	Soil physical characteristics	0.09
Stand density	Soil chemistry characteristics	0.35
	Soil physical characteristics	0.20
	Species diversity	0.44
Stand structures	Soil chemistry characteristics	0.13
	Soil physical characteristics	0.09
	Species diversity	0.70
	Stand density	0.09

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Discussion

Characteristics of understory herbaceous community in different plantations

Understory herbaceous plants constitute the foundation of plantation ecosystems (Horvat et al., 2017). As sensitive components within these ecosystems, understory herbs are particularly influenced by their surroundings (Liu et al., 2022). Due to the unique stand structure and growth, different plantations form different canopy morphology and microenvironmental characteristics in the forest, which affect the light and soil nutrients of understory herbs (Eisenhauer et al., 2011; Rawlik et al., 2018). Therefore, the composition and distribution of herbs in the six plantations were different. *Asteraceae* accounted for the largest proportion of 41.18% due to its drought tolerance, rapid seed dissemination, and strong adaptability to the environment and reproduction ability (Hao et al., 2009).

In this study, the number of understory herbaceous plants was the highest in *Rop* plantation. The M, D, H and J_{sw} of *Rop* were significantly higher than those in other plantations. This indicated that the understory herbaceous diversity in *Rop* was the highest, which is conducive to the sustainable development of these plants. This may be attributed to the presence of Rhizobia in the roots of *Rop*. Rhizobium can fix N from the air, improve soil nutrients, increase soil microbial diversity, and promote the survival of understory herbs. Additionally, the stand density of *Rop* was appropriate, and the contents of SOC, TN and TP in soil were high, all of which are conducive to the growth of understory herbs. Conversely, in this study, the M and H of *Frc* were the lowest, and the D and J_{sw} of *Ulp* were smaller than those for other plantations. These differences were induced by the stand density. Specifically, the stand density of *Ulp* and *Frc* were high, and previous studies have found that the stand density is negatively correlated with the understory herb diversity (Ali et al., 2019). High stand density results in high crown density, which reduces light penetration to the herbaceous layer, inhibits the growth of light-loving herbaceous species, and ultimately leads to a decrease in the number of herbaceous species in *Ulp* and *Frc*. Regarding *Stj*, the M, D and H of were relatively high, but its J_{sw} was the lowest. This may be due to the complex environment and fierce competition among the understory herbaceous species in *Stj* within our study area. Although these species are relatively abundant in *Stj*, the individual number distribution is uneven (Gao et al., 2022).

Effect of different plantations on soil physicochemical characteristics

Soil physical and chemical characteristics serve as the foundation for plant diversity, influencing species composition and community structure (Cazzolla Gatti et al., 2015). The six plantations selected for this study exhibited differences in soil physical and chemical characteristics, suggesting that the community structure and species composition of these plantations have a significant impact on the soil properties. The CP and NCP of the soil were both excellent, potentially due to the special root system of *Act*. This well-developed root system is associated with two kinds of mycorrhiza (Wang, 1996), enhancing soil root activity. Consequently, the soil structure became looser, porosity increased, and bulk density decreased, which were beneficial for improved soil aeration and water retention (Ding et al., 2021). The SOC and TN contents were the highest in *Ulp*. This is mainly attributed to the fact that soil nutrients primarily originate from plant litter, which is significantly influenced by the nature and quantity of the litter (Nave et al., 2013; Wang et al., 2021). Furthermore, the *Ulp* had

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the highest stand density, resulting in a large amount of litter. This large litter is conducive to the accumulation of organic carbon and other soil nutrients. In this study, all soil nutrient indexes of the *Rop* were excellent, except for AN. This is attributed to the high plant diversity, high community productivity, and abundant plant roots and litter in the soil of *Rop*, leading to higher nutrient content (Zheng et al., 2019; Chen et al., 2020). In addition to TP, soil nutrients in the plantations showed obvious surface aggregation. This was primarily due to the vertical distribution of soil nutrients being influenced by the leaching, migration, and deposition of organic matter and humus. Plant litter decomposed in the surface soil, with part being absorbed and utilized by plant roots and the other part remaining in the surface soil. As soil depth increased, litter and plant and animal residues continued to decrease, resulting in a decreasing trend in soil nutrients. This conclusion is consistent with previous studies (Tian et al., 2017). When compared with the classification standards of the Second National Soil General Survey, the SOC, TN, and AN in the 6 plantations were found to be low, and TP was extremely low. This indicates that the plantations in the study area are deficient in soil nutrients. Therefore, conservation and management efforts for these plantations should focus on soil nutrient management. These findings are consistent with the research results of other scholars (Meng et al., 2023; Ren, et al., 2025).

The dominant factor analysis of understory herbaceous importance values and species diversity

The importance value represents the degree of dominance of a species in the community and serves as a key indicator for measuring the status of a species. This study identifies AN, SOC, BD, SWC, and NCP as the key soil factors influencing the distribution of understory herbaceous species. AN and SOC are the most significant soil nutrient factors affecting the distribution of understory herbs. Soil organic carbon decomposition products constitute important sources of plant nutrients, with AN being the nitrogen form in soil that plants can readily absorb and utilize. Herbs with higher water and fertilizer requirements tend to distribute more in habitats characterized by higher SOC and AN content (Dubey et al., 2021; Hu et al., 2021). In this study, as SOC increased, the number of understory herb species also increased. However, with an increase in soil AN, the number of understory herb species did not change significantly. This observation is linked to the strategies employed by herbaceous plants for utilizing carbon and nitrogen sources. Herbs absorb organic carbon from the soil, while leguminous herbs can not only absorb and obtain nitrogen sources directly from the soil but also cooperate with nitrogen-fixing bacteria (Andrews and Andrews, 2017; Sachs et al., 2018). This cooperation gives them a competitive advantage, especially when soil nitrogen is limited. Previous studies have demonstrated that SWC significantly influences the spatial distribution pattern of species by integrating various environmental factors, such as temperature and humidity (Wasie et al., 2020). This finding is consistent with the conclusions of the present study. In our study, as BD decreases, SWC and NCP tend to increase. Consequently, the species diversity of understory herbs gradually increases. This is primarily attributed to the loosened soil and adequate water, which promote the growth and distribution of competitive plants, leading to high community richness (Hu et al., 2021).

Further, a PLS-SEM was used to comprehensively analyze the factors affecting understory herbaceous diversity, including stand density, stand structure, and soil physicochemical properties, after RDA screening. It was found that stand structure was

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the key driving factor of understory herbaceous M and J_{sw}, this finding being consistent with the research results of Cook et al. (2015). Many previous studies have shown that stand structure not only reflects the growth status of trees, but also further affects the distribution and growth of herbs in the understory by altering the understory microenvironment (Rawlik et al., 2018; Tinya et al., 2021). This study showed that DBH, tree height, and crown length were positively correlated with understory herbaceous diversity, primarily due to the following reasons: (1) As the tree size increases, the temperature and humidity conditions in the community improve, forming a microenvironment required for the growth of specific understory vegetation (Augusto et al., 2003); (2) Stands with larger DBH may offer more niche space for species in the understory that occupy different ecological niches, thereby promoting species coexistence and diversity (Bartels et al., 2010; Guo et al., 2021); (3) The increase of DBH may lead to the decrease of light under the forest. However, for some species that are shade tolerant, it is more conducive to their growth (Trettin et al., 2011). At the same time, a larger DBH may indicate that trees are more competitive for soil nutrients and water, which may have a negative impact on some resource-demanding understory species. While some more adaptable species may be able to survive in this competitive environment, their presence contributes to the diversity of understory herbaceous species (Roberts et al., 2014). Eduardo et al.'s study in central Iberian Peninsula found that abiotic factors, such as soil water content and light conditions are critical drivers of understory herb diversity (Mezquida et al., 2025). The PLS-SEM also shows that the path coefficients of stand density on soil AN and stand structure are −0.359 and −0.068, respectively, aligning with the previous studies (Zhang et al., 2019). This is because as stand density increases, the canopy occlusion of trees also rises. Consequently, this occlusion affects the photosynthesis of tree leaves, ultimately having a negative impact on tree growth. Increasing stand density also reduces the light in the forest and impacts the decomposition of litter facilitated by soil enzymes, subsequently decreasing the availability of nutrients in the soil (Deng et al., 2023).

Conclusions

Our study revealed that that the study area harbored 34 species of understory herbs, predominantly belonging to the *Asteraceae* family. The dominant species were *Cirsium setosum*, *Artemisia argyi, Digitaria sanguinalis* and *Artemisia scoparia*. *Rop* exhibited the highest species diversity of understory herbs. We identified AN, SOC, BD, SWC and NCP as the key soil factors influencing the distribution of understory herbaceous species. Additionally, stand structure characteristics such as crown length, DBH and tree height were the key drivers of M and J_{sw} in understory herbaceous species. This study characterized the understory herbaceous communities in different plantations in the Beijing Plain and elucidated the main driving factors of understory herbaceous diversity across these plantations. To effectively maintain the stability of the artificial forest ecosystem in the Beijing Plain area, we suggest focusing on optimizing the stand structure while considering the comprehensive effects of soil conditions and stand density.

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