Stand Structure and Soil Physicochemical Properties of Slash Pine–Chinese Tulip Tree Mixed Plantations in Rocky Desertification Areas of Western Hunan (Postprint)

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Abstract

To investigate the stand structure and soil physicochemical properties of slash pine–Chinese tulip tree mixed plantations in the rocky desertification area of western Hunan, this study analyzed an artificial coniferous-broadleaved mixed forest of slash pine (Pinus elliottii) and Chinese tulip tree (Liriodendron chinense) using phytocoenological analysis and field sampling methods, calculated stand spatial structure parameters using Winklemass 1.0, and analyzed spatial distribution patterns of dominant species using three-dimensional discrete random variables. The results showed that: (1) There were 897 plants $\cdot$ hm^{-2} with DBH $\geq$ 2 cm in the stand, belonging to 15 families and 16 genera. The main canopy layer was dominated by slash pine, with an average DBH of 32.3 cm and an importance value of 44.2%; the sub-canopy layer consisted of broadleaved trees, mostly middle-aged and young individuals, among which camphor tree (Cinnamomum camphora) and Chinese tulip tree were the dominant species with importance values of 17.1% and 13.2%, respectively. Additionally, there were many naturally regenerated species occupying disadvantageous ecological niches. (2) The horizontal distribution pattern of trees tended toward random distribution (=0.503); the overall stand showed a trend transitioning from intermediate to disadvantageous status (=0.505); the degree of interspecific segregation was high (=0.689), indicating good mixing conditions among trees. The three-dimensional discrete random variable of spatial structure parameters revealed that 87.3% of slash pines were in dominant and co-dominant positions, 41.7% of Chinese tulip trees were co-dominant and 26.9% were in intermediate status, while 23.5% of camphor trees were in intermediate status and 56.8% were in disadvantageous and absolutely disadvantageous positions. (3) The soil pH value in the stand tended to be neutral; compared with abandoned land, soil factors such as bulk density, water holding capacity, porosity, organic carbon, total potassium, total nitrogen, and total phosphorus in the stand were significantly improved. However, overall, the stand soil remained relatively infertile, with locally compacted soil and poor water retention capacity. In summary, after 43 years of growth as pioneer species, slash pine and Chinese tulip tree showed a trend toward succession to uneven-aged forest and intensively mixed forest. However, the proportion of middle-aged and young broadleaved trees in the stand was relatively large, a gap appeared in the near-mature forest, and old-aged coniferous trees occupied advantageous ecological positions. Therefore, it is necessary to selectively harvest conifers and supplement with broadleaved trees, thin conifers to cultivate broadleaved trees, and selectively cut disadvantageous trees to promote stand succession toward a structure dominated by heliophilous broadleaved trees, with mesophytic and shade-tolerant broadleaved trees as secondary components. The results of this study provide a theoretical basis for vegetation restoration, artificial forest structure optimization, and soil improvement in this region.

Full Text

Study on the Stand Structure and Soil Physicochemical Properties of Artificial Mixed Forests of *Pinus elliottii* and *Liriodendron chinense* in the Rocky Desertification Area of Western Hunan

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Abstract: Taking the artificial coniferous-broadleaved mixed forest of *Pinus elliottii* and *Liriodendron chinense* in the rocky desertification area of western Hunan as the research object, this study analyzed stand structure and soil physicochemical properties using plant community analysis and field sampling methods. Winkelmass 1.0 was employed to calculate stand spatial structure parameters, and three-dimensional discrete random variables were used to analyze the spatial distribution patterns of dominant species. The results showed that: (1) There were 897 trees$\cdot$hm^{-2} with DBH $\geq$ 2 cm in the stand, belonging to 15 families and 16 genera. The main canopy layer was *P. elliottii* with an average DBH of 32.3 cm and an importance value of 44.2%; the sub-canopy layer consisted of broadleaved trees, predominantly young and middle-aged, with *Cinnamomum camphora* and *L. chinense* as dominant species having importance values of 17.1% and 13.2%, respectively. Additionally, numerous naturally regenerated species occupied disadvantaged niches. (2) The horizontal distribution pattern tended toward random distribution (W = 0.503), while the overall stand showed a transitional state from medium to disadvantaged status (U = 0.505). Interspecific isolation was relatively high (M = 0.689), indicating good mixing conditions. Three-dimensional discrete random variables of spatial structure parameters revealed that 87.3% of *P. elliottii* were dominant or subdominant, 41.7% of *L. chinense* were subdominant and 26.9% were in medium status, while 23.5% of *C. camphora* were in medium status and 56.8% were disadvantaged or absolutely disadvantaged. (3) Soil pH tended toward neutrality. Compared with abandoned land, soil bulk density, water-holding capacity, porosity, organic carbon, total potassium, total nitrogen, and total phosphorus all improved significantly. However, overall stand soil remained relatively infertile with local compaction and poor water retention capacity. In summary, after 43 years of growth as pioneer species, *P. elliottii* and *L. chinense* showed succession trends toward uneven-aged and intensively mixed stands. However, the proportion of young and middle-aged broadleaved trees was large, near-mature stands showed gaps, and aged conifers occupied advantageous ecological positions. Management strategies including thinning conifers to supplement broadleaved species, interplanting conifers with broadleaved species, and selective removal of disadvantaged trees are needed to promote succession toward a structure dominated by heliophilous broadleaved trees with secondary mesophytic and shade-tolerant broadleaved species. These results provide a theoretical basis for vegetation restoration, plantation structure optimization, and soil improvement in this region.

Keywords: rocky desertification, artificial mixed forest of *Pinus elliottii* and *Liriodendron chinense*, stand composition, stand spatial structure, soil physicochemical properties

The Wuling Mountains in western Hunan were formed by the collision of the Indian and Eurasian plates in the late Tertiary period. Elevated topography caused abrupt environmental changes and intense soil erosion, while anthropogenic factors such as deforestation and agricultural cultivation further disrupted regional ecological balance (Zhu et al., 2020), making rocky desertification an extremely severe ecological issue in southwestern China that constrains local social, economic, and cultural development (Chen et al., 2020). Ecosystems in rocky desertification areas are highly fragile; once original vegetation is destroyed, ecological restoration becomes extremely difficult (Pu et al., 2020). Moreover, rocky desertification exacerbates soil erosion and bedrock exposure, causing persistent deficits of soil nutrients and moisture near exposed rocks (Sun et al., 2018) and leading to gradual or complete loss of forest productivity (Li et al., 2020). Due to this ecological vulnerability, vegetation restoration and reconstruction have become central challenges in ecological management of rocky desertification areas in southwestern China (Zhang et al., 2015). However, low soil carrying capacity and limited environmental capacity in these areas restrict vegetation growth and development (Zhang et al., 2015), resulting in persistent problems such as low seedling survival rates and poor stand quality after canopy closure during long-term ecological restoration and forest management (Li and Yu, 2009).

Forest basic functions are closely related to stand quality, which significantly influences forest ecosystem stability and sustainable management (Tao et al., 2020). Stand spatial structure comprises structural units formed by the attributes and ecological positions of target trees and their neighbors, serving as a driving factor in forest growth and succession. Quantitative analysis of stand spatial structure parameters can accurately describe spatial distribution patterns, competitive relationships, and interspecific associations among trees, enabling assessment of stand quality and growth potential for use as key decision-making indicators in forest management (Bai, 2016). Soil physicochemical properties reflect the integrated effects of parent material, environmental factors, and biological characteristics, influencing vegetation establishment, development, and succession while being reciprocally affected by community structure and the quantity and quality of litter (Yuan et al., 2019). Vegetation restoration in rocky desertification areas determines the effectiveness of soil improvement, as litter decomposition and deposition help alleviate soil moisture and nutrient limitations, eventually forming a coordinated ecosystem among vegetation, soil, water, and bedrock (He et al., 2020; Huang et al., 2021). Therefore, analyzing vegetation restoration effects through stand spatial structure and developing optimization strategies are crucial for maintaining and improving forest ecosystem stability and soil conditions (Yang et al., 2019).

This study examined an artificial coniferous-broadleaved mixed forest of *Pinus elliottii* and *Liriodendron chinense* in the rocky desertification area of western Hunan, analyzing species composition, diameter distribution, stand spatial structure characteristics, and soil physicochemical properties to address three questions: (1) What are the vegetation structural characteristics of *P. elliottii*–*L. chinense* plantations after succession in western Hunan's rocky desertification areas? (2) What is the response mechanism between coniferous-broadleaved mixed forest establishment and soil factors in rocky desertification areas? (3) What recommendations can be proposed for future plantation structure optimization and vegetation restoration in these areas? This research aims to provide a theoretical basis for ecological restoration in rocky desertification regions.

1.1 Study Site and Stand Description

The Wuling Mountains Rocky Desertification Comprehensive Control National Long-term Research Base (110°13 E, 29°3 N) is located in Qingping State-owned Forest Farm, Yongshun County, northwestern Hunan Province, at 320–820 m elevation. Soils are primarily red-yellow earth with variable depth. The climate features southeast monsoons and mid-subtropical humid conditions, with mean annual precipitation of 1,300–1,500 mm, mean annual sunshine of 1,240–1,440 h, and mean annual temperature of 15.8–16.9 °C. Ecological restoration began in the early 1960s, and afforestation efforts have achieved remarkable success.

The study site, formerly called “Maoshanpo” (meaning “mountain covered with thatch and rocks”), was planted in 1978 on a 15° slope at 467 m elevation. The species configuration used interplanting of *Pinus elliottii* and *Liriodendron chinense* at a 7:3 ratio, with 2.5 m row spacing and initial planting density of 1,600 plants $\cdot$ hm^{-2}. After years of management and natural regeneration, the stand exhibited excellent growth with canopy closure above 0.85.

In July 2021, four 0.16 hm^2 standard plots (S1, S2, S3, S4) were established and subdivided into sixteen 10 m × 10 m subplots using the adjacent grid method, with a plane rectangular coordinate system established at the lower-left corner of each grid. All trees with DBH $\geq$ 2 cm were measured, recording species, DBH, height, crown width, XY coordinates, and assigned numbered tags. At three points spaced 20 m apart in each plot, surface litter and humus were removed, and soil samples were collected from 0–15 cm, 15–30 cm, and 30–50 cm depths using a spiral auger and ring sampler (Edelman model, Germany; ring specifications $D = 50.46$ mm, $H = 50$ mm, $V = 100$ cm^3) to determine soil water-physical properties. Approximately 500 g of soil from each point was bagged, impurities removed, air-dried, and ground for chemical analysis. Three 20 m × 20 m replicate plots were established in abandoned land (CK) using the same soil sampling method.

1.3 Species Importance Value Calculation

Curtis and McIntosh (1951) first proposed the “importance value” as a comprehensive indicator reflecting a plant’s function and status in a community. Using quadrat survey methods, tree count, DBH, and height parameters were obtained to calculate relative abundance, relative frequency, relative dominance, and importance value (Feng et al., 2021).

1.4 Stand Spatial Structure Analysis

Spatial structure units composed of four adjacent trees were used to analyze stand spatial structure information. The uniform angle index analyzed horizontal distribution patterns, dominance index assessed relative size differences, and mingling index evaluated species spatial configuration and isolation degree (Hui and Gadow, 2003).

Table 1 Calculation formulas and descriptions of stand spatial structure indices

Index	Formula	Description
Uniform angle (W)	$W_i = \frac{1}{n}\sum_{j=1}^{n} Z_{ij}$, $\bar{W} = \frac{1}{N}\sum_{i=1}^{N} W_i$	Z_{ij} represents the relationship between angle α formed by reference tree i and neighbor j and the standard angle α_0 ($\alpha_0 = 72°$). When $\alpha > \alpha_0$, $Z_{ij} = 0$; otherwise $Z_{ij} = 1$. W_i has five values: 0, 0.25, 0.5, 0.75, and 1, corresponding to absolute uniform, uniform, random, non-uniform, and absolute non-uniform patterns; $\bar{W}$ indicates the community-level horizontal distribution pattern. In this study, $n = 4$ and N is the total number of trees in the sample plot (same below).
Dominance (U)	$U_i = \frac{1}{n}\sum_{j=1}^{n} K_{ij}$, $\bar{U} = \frac{1}{N}\sum_{i=1}^{N} U_i$	K_{ij} represents the size relationship between reference tree DBH i and neighbor DBH j. When $i > j$, $K_{ij} = 0$; otherwise $K_{ij} = 1$. U_i has five values: 0, 0.25, 0.5, 0.75, and 1, corresponding to dominant, subdominant, medium, inferior, and absolutely inferior; $\bar{U}$ reflects the proportion of dominant trees at the community level.
Mingling (M)	$M_i = \frac{1}{n}\sum_{j=1}^{n} V_{ij}$, $\bar{M} = \frac{1}{N}\sum_{i=1}^{N} M_i$	V_{ij} represents the identity relationship between reference tree i and neighbor j. When i and j are the same species, $V_{ij} = 0$; otherwise $V_{ij} = 1$. M_i has five values: 0, 0.25, 0.5, 0.75, and 1, corresponding to zero, weak, moderate, strong, and extremely strong mixing; $\bar{M}$ can be used to determine the degree of mixing at the community level.

1.5 Three-Dimensional Discrete Random Variable Distribution

Analyzing stand spatial structure using joint probability of three-dimensional discrete random variables can more intuitively reveal the spatial status of individual species (Wu et al., 2019). The average mingling index, uniform angle index, and dominance index of dominant trees from four plots were cross-combined to generate 125 three-dimensional discrete random variables (X, Y, Z), and 3D stacked bar charts of dominant species spatial structure parameters were plotted.

1.6 Soil Physicochemical Property Measurement

Soil physical properties including bulk density, maximum water-holding capacity, minimum water-holding capacity, capillary porosity, and total porosity were determined according to the *Forestry Industry Standard of the People's Republic of China – Forest Soil Analysis Methods* (State Forestry Administration, 2000). Soil chemical properties including pH, organic carbon, total nitrogen, total phosphorus, and total potassium were measured using methods from *Agrochemical Analysis of Soil* (Bao, 2011).

1.7 Data Statistical Analysis

Data were processed using Microsoft Office Excel 2016, descriptive analysis was conducted using SPSS 26, and Winkelmass 1.0 was used for spatial structure analysis.

2.1 Species Composition Characteristics of the Coniferous-Broadleaved Mixed Forest

The stand contained 897 trees $\cdot\,\mathrm{hm}^{-2}$ with DBH ≥ 2 cm, belonging to 15 families and 16 genera. The main canopy layer consisted of *Pinus elliottii* (259 trees $\cdot\,\mathrm{hm}^{-2}$) with an average DBH of 32.3 cm, average height of 23.5 m, relative dominance of 77.7%, and importance value of 44.2%, indicating excellent growth, mature to overmature age, high timber volume, and absolute dominance in the stand. The sub-canopy layer comprised broadleaved trees, predominantly young and middle-aged, with *Liriodendron chinense* averaging 12.9 cm DBH and 14.9 m height (importance value 13.2%), demonstrating good growth and natural regeneration. *Cinnamomum camphora* had an average DBH of 10.9 cm, average height of 10.7 m, relative abundance of 22.3%, and importance value of 17.1%. As a naturally regenerated species, *C. camphora* widely established throughout the site due to its superior reproductive capacity and stress resistance. Other naturally regenerated broadleaved species including *Vernicia fordii*, *Castanea mollissima*, *Melia azedarach*, and *Camptotheca acuminata* totaled 269 trees $\cdot\,\mathrm{hm}^{-2}$. Their seeds dispersed over long distances from corresponding stands within the base, and influenced by site conditions and competition, these species occupied disadvantaged niches but filled canopy gaps, forming a more ecologically stable coniferous-broadleaved mixed uneven-aged stand. Additionally, occasional individuals with DBH < 2 cm, regenerated saplings, and woody lianas occurred in the understory, increasing humidity and species diversity while stabilizing community structure.

Table 2 Tree species composition of the tree layer in sample plots

Species	Relative dominance (%)	Relative abundance (%)	Relative frequency (%)	DBH (cm)	Height (m)	Importance value (%)
Pinus elliottii	77.7	28.9	25.6	32.3	23.5	44.2
Cinnamomum camphora	4.3	22.3	25.6	10.9	10.7	17.1
Liriodendron chinense	5.1	15.7	20.1	12.9	14.9	13.2
Vernicia fordii	2.9	8.5	7.8	9.8	9.3	6.4
Camellia oleifera	2.1	6.8	5.2	8.7	8.1	4.7
Castanea mollissima	2.4	5.2	6.5	11.2	10.2	4.7
Melia azedarach	1.8	4.2	4.3	10.5	9.8	3.4
Bothrocaryum controversum	1.2	3.1	2.9	9.1	8.5	2.4
Prunus pseudocerasus	0.9	2.1	2.1	8.9	8.3	1.7
Camptotheca acuminata	0.7	1.8	1.9	9.5	8.9	1.5
Michelia maudiae	0.4	1.2	1.3	8.4	7.8	1.0

Species	Relative dominance (%)	Relative abundance (%)	Relative frequency (%)	DBH (cm)	Height (m)	Importance value (%)
Kalopanax septemlobus	0.3	0.8	1.0	10.1	9.2	0.7
Elaeocarpus decipiens	0.2	0.5	0.7	7.9	7.2	0.5
Alangium chinense	0.1	0.3	0.4	8.2	7.5	0.3
Rhamnus davurica	0.1	0.2	0.3	7.6	6.9	0.2
Choerospondias axillaris	0.1	0.1	0.2	8.8	8.1	0.1

2.2 Stand Diameter and Height Structure Characteristics

Using 2 cm and 2 m as classification intervals for DBH and height analysis (Fig. 1 [Figure 1: see original paper]), the stand exhibited DBH ranges of 2–55 cm and height ranges of 2.5–28 m, both showing bimodal distributions. Trees with DBH of 4–16 cm accounted for 67.2% of the total, comprising 19.3% *Cinnamomum camphora*, 15.7% *Liriodendron chinense*, and 28.0% other broadleaved species. Few broadleaved trees exceeded 20 cm DBH. In contrast, 23.3% of *Pinus elliottii* exceeded 28 cm DBH, with 9.58% of the stand's total trees being *P. elliottii* > 40 cm DBH, though natural regeneration of *P. elliottii* was scarce. Trees < 16 m tall were primarily young and middle-aged *C. camphora*, *L. chinense*, and other broadleaved species (61.7% of total trees), while trees > 16 m were mostly *P. elliottii* (23.9% of total). Both diameter and height structures indicated a large proportion of young and middle-aged trees, gaps in near-mature stands, and only *P. elliottii* populations reaching mature to overmature stages, necessitating appropriate artificial interventions to coordinate interspecific relationships and promote succession toward more stable forest communities.

2.3 Stand Spatial Structure

As shown in Fig. 2 [Figure 2: see original paper], the relative frequency at W = 0.5 was 0.614, indicating random distribution as the predominant pattern. Relative frequencies at W = 0, 0.25, 0.75, and 1 were 0, 0.214, 0.119, and 0.053, respectively, showing no absolutely uniform individuals and that uniform, non-uniform, and absolutely non-uniform distributions accounted for 38.6% of trees. The mean uniform angle index was 0.503. According to the criteria of W <

0.475 for uniform, $0.475 \leq W \leq 0.517$ for random, and $W > 0.517$ for clumped distribution (Wang et al., 2012), the stand showed a random distribution pattern.

Size ratio index showed relatively uniform proportions across all levels, indicating evenly distributed trees of different diameter classes among structural units. The mean size ratio index was 0.505, suggesting moderate overall differentiation and a medium status. However, the proportion of inferior (U = 0.220) and absolutely inferior trees (U = 0.206) slightly exceeded that of dominant (U = 0.220) and subdominant trees (U = 0.172), indicating a transitional state from medium to disadvantaged status.

In the mingling distribution frequency, relative frequencies at M = 0.25, 0.5, 0.75, and 1 were 0.127, 0.224, 0.336, and 0.293, respectively, while M = 0 was only 0.020. Strong and extremely strong mixing clearly exceeded weak and moderate mixing, with zero mixing absent, indicating high mingling among individual trees. The mean mingling index M = 0.689 showed moderate-to-strong mixing at the stand level, high interspecific isolation, and reasonable interspecific competition conducive to community stability.

2.4 Three-Dimensional Distribution Characteristics of Spatial Structure Parameters

As shown in Fig. 3a [Figure 3: see original paper], when uniform angle and size ratio indices remained constant, relative frequency distribution increased with mingling index. *Pinus elliottii* relative frequencies were primarily distributed at W = 0.5, M = 0.75, and M = 1 (0.741, 0.318, and 0.427, respectively), indicating 74.1% showed random distribution and 74.5% exhibited strong and extremely strong mixing. Relative frequencies at U = 0 and U = 0.25 were 0.633 and 0.239, respectively, showing 87.2% of *P. elliottii* were dominant or subdominant with clear competitive advantages. The highest cumulative relative frequency occurred at W = 0.5 and M = 1 (0.317), with the maximum at W = 0.5, M = 1, U = 0 (0.201), indicating 20.1% of *P. elliottii* simultaneously exhibited random distribution, extremely strong mixing, and absolute dominance.

As shown in Fig. 3b, *Cinnamomum camphora* relative frequencies were clearly distributed at W = 0.25 and W = 0.5 (0.268 and 0.607, respectively), indicating 26.8% showed uniform distribution and 60.7% random distribution, reflecting relatively uniform horizontal patterns related to seed dispersal characteristics. When uniform angle and mingling indices remained constant, size ratio indices were primarily distributed at U = 0.5, 0.75, and 1 (0.235, 0.302, and 0.266, respectively), showing 23.5% in medium status and 56.8% in disadvantaged or absolutely disadvantaged niches. At M = 0.75 and M = 1, relative frequencies were 0.457 and 0.222, respectively, indicating 67.9% showed strong and extremely strong mixing. The highest cumulative relative frequency occurred at M = 0.75 and W = 0.5 (0.278), showing 27.8% of *C. camphora* simultaneously exhibited strong mixing and random distribution.

As shown in Fig. 3c, *Liriodendron chinense* relative frequencies were concentrated at W = 0.5 and M = 1 (0.765 and 0.629, respectively), indicating 76.5% showed random distribution and 62.9% extremely strong mixing. When size ratio index remained constant, the cumulative relative frequency at W = 0.5 and M = 1 was 0.481, showing 48.1% of *L. chinense* simultaneously exhibited random distribution and extremely strong mixing. The highest relative frequency occurred at W = 0.5, M = 1, U = 0.25 (0.200), followed by W = 0.5, M = 1, U = 0.5 (0.129), indicating that among trees showing random distribution and extremely strong mixing, 20% were subdominant and 12.9% were in medium status.

2.5.1 Soil Physical Properties

Soil bulk density in both sample plots and abandoned land increased with depth (Fig. 4 [Figure 4: see original paper]a). Compared with abandoned land, surface soil bulk density in sample plots improved significantly due to litter decomposition and accumulation, while deep soil became relatively compacted from root pressure. Both sample plots and abandoned land showed high local bulk density, likely caused by numerous small rock particles from weathered bedrock in rocky desertification areas. Mean values for sample plot soil maximum water-holding capacity, minimum water-holding capacity, capillary porosity, and total porosity were 30.34%, 24.24%, 33.15%, and 40.18%, respectively (Fig. 4b–e), all higher than abandoned land, particularly for surface soil water-physical properties, indicating that positive anthropogenic promotion of vegetation succession improved soil water-physical properties. However, overall water-holding, infiltration, and gas exchange capacities remained poor, with considerable room for improvement in water-holding performance and porosity.

2.5.2 Soil Chemical Properties

Soil pH in sample plots ranged from 5.09 to 7.87 with a mean of 6.70, tending toward neutrality and significantly higher than abandoned land at all depths ($P < 0.05$) (Fig. 4f). While southern soils are generally acidic, the higher pH in sample plots was closely related to severe rocky desertification, likely due to abundant carbonate compounds in limestone areas hydrolyzing to produce bicarbonate and hydroxide ions. Soil organic carbon content decreased with depth in both sample plots and abandoned land, with 0–15 cm soil in sample plots (mean 19.11 $g \cdot kg^{-1}$) significantly higher than other layers ($P < 0.05$), showing clear surface accumulation (Fig. 4g). The coefficient of variation for soil organic carbon was 70.09% in sample plots and 63.37% in abandoned land, indicating extremely uneven distribution in this rocky desertification area. Mean contents of total nitrogen, total phosphorus, and total potassium in sample plots were 1.22, 0.32, and 26.15 $g \cdot kg^{-1}$, respectively, all higher than abandoned land (0.93, 0.23, and 18.56 $g \cdot kg^{-1}$). Total nitrogen in 0–15 cm soil (mean 1.73 $g \cdot kg^{-1}$) was significantly higher than in deeper layers ($P < 0.05$). Overall soil chemical properties in the stand were superior to abandoned land, indicating that artificial forest establishment in rocky desertification areas had greater accumulation effects on soil organic carbon, total nitrogen, total phosphorus, and total potassium than abandoned shrub-grassland.

3 Discussion

Vegetation composition and stand structure are fundamental forest characteristics that reflect inter-tree relationships and responses to environmental conditions (Ding et al., 2015). Currently, *Pinus elliottii* dominates the main canopy layer of the uneven-aged stand as mature or overmature large-diameter timber, occupying an absolutely advantageous niche—attributes related to its strong adaptability, drought and infertility tolerance, and lack of buffering period in early growth (Ma et al., 2011). *Cinnamomum camphora* had the second-highest importance value, establishing extensively in canopy gaps and rock crevices through superior reproductive capacity, though primarily as young and middle-aged trees limited by the infertile rocky desertification site conditions (Li and Nie, 2011). Additionally, substantial mid-aged *Liriodendron chinense* regeneration occurred, contrasting with previous studies reporting extremely low seed viability due to poor synchronization of pistil and stamen flowering, with germination rates below 5.0% for isolated individuals and 31.8% in group settings, and shade-intolerant seedlings typically restricted to forest gaps or edges (Huang, 1998; Li and Ma, 2003; Feng et al., 2011). The mid-aged *L. chinense* in this study likely resulted from the 2008 southern China ice disaster, as low temperatures facilitate seed stratification and germination while destroying upper canopy layers to provide light and growth space for lower regeneration. Furthermore, ongoing stand succession increased species richness through natural regeneration of additional species and understory vegetation, creating a relatively stable forest ecosystem after canopy closure.

Stand spatial structure parameters quantitatively analyze tree dominance and ecological positions, comprehensively reflecting stand characteristics. Generally, optimal spatial structure features random horizontal distribution, moderate-to-strong mixing, and greater proportions of dominant trees, resulting in stronger functionality and higher stability (Chen et al., 2015; Peng et al., 2016). This study found random horizontal distribution patterns, moderate-to-strong mixing, high mingling, and a transitional state from medium to disadvantaged status, consistent with Yuan et al. (2022) on *Cinnamomum camphora–Pinus elliottii* mixed plantations in western Hunan's rocky desertification areas. Future forest quality improvement should consider natural regeneration and stand structure characteristics, targeting clumped distributions ($W > 0.75$) and zero-to-weak mixing trees for selective removal to promote random distribution and moderate-to-strong mixing, while thinning overstory, dead, and crooked trees to coordinate interspecific relationships (Han et al., 2019). Three-dimensional distribution of spatial structure parameters showed *P. elliottii* as absolutely dominant, *L. chinense* as secondary, and *C. camphora* in medium or disadvantaged niches. However, *P. elliottii* showed obvious aging, suggesting future succession will likely produce a forest structure dominated by *L. chinense* and *C. camphora* coexisting with naturally regenerated mesophytic or shade-tolerant broadleaved species (Li et al., 2021).

Forest soils are influenced by parent material, climate, topography, and precipitation, continuously changing with biological factors (Ma et al., 2020). Karst region soils typically feature exposed bedrock, shallow soil layers, poor water retention, and calcium enrichment (Li et al., 2002). This study's neutral soil pH was closely related to abundant carbonate compounds in limestone areas. Compared with abandoned land, increased soil organic carbon, total nitrogen, total phosphorus, and total potassium resulted from atmospheric deposition uptake during stand growth and accelerated nutrient return through litter decomposition (Zeng et al., 2015). Chen et al. (2022) also demonstrated that increasing species numbers gradually improved soil properties under rocky desertification conditions in western Hunan. Liu et al. (2022) revealed that coniferous-broadleaved mixed forests improved soil fertility better than pure coniferous stands in this region. Additionally, strong spatial heterogeneity in soil physicochemical properties was consistent with Sheng et al. (2015), as exposed bedrock created a "fence effect" concentrating decomposed litter around rocks. However, the soil showed characteristics of "nitrogen and phosphorus deficiency with potassium enrichment" (National Soil Census Office, 1992), likely due to long-term leaching losses of nitrogen and phosphorus in the subtropical monsoon climate with hot, rainy summers, where deposited nitrogen undergoes nitrification and denitrification, losing N_2O, while low phosphorus results from soil phosphorus fixation mechanisms and potassium enriches as soluble forms (Fang et al., 2004; Li et al., 2019). Overall, soil fertility remained relatively poor with local compaction and bedrock exposure negatively affecting root extension, water-gas infiltration, and water-holding capacity, yet *P. elliottii*, *L. chinense*, and *C. camphora* grew well, attributable to the warm site conditions in western Hunan and previous intensive site preparation.

4 Conclusion

Analysis of stand structure and soil physicochemical properties of the *Pinus elliottii–Liriodendron chinense* mixed plantation in western Hunan's rocky desertification area revealed: (1) The main canopy layer consisted of *P. elliottii* as large-diameter trees with 44.2% importance value. The sub-canopy layer comprised broadleaved trees, predominantly young and middle-aged, with *Cinnamomum camphora* and *L. chinense* as dominant species (importance values 17.1% and 13.2%, respectively) and numerous naturally regenerated species in disadvantaged niches. (2) Horizontal distribution was random, stand dominance showed a transitional state from medium to disadvantaged, most trees exhibited moderate-to-strong mixing with high interspecific isolation, and the stand showed succession trends toward uneven-aged, intensively mixed structure after decades of growth. (3) However, the large proportion of young and middle-aged broadleaved trees, gaps in near-mature stands, and absolute dominance of aged conifers in advantageous positions require management strategies of thinning conifers to supplement broadleaved species, interplanting conifers with broadleaved species, and selective removal of disadvantaged trees to promote succession toward a structure dominated by heliophilous broadleaved trees with secondary mesophytic and shade-tolerant broadleaved species. (4) Soil physicochemical properties improved compared with abandoned land, but overall fertility remained poor with local compaction and bedrock exposure negatively affecting root extension, water-gas infiltration, and water-holding capacity, requiring further improvement. In future rocky desertification management in western Hunan, *P. elliottii*, *L. chinense*, and *C. camphora* can be promoted as pioneer species for ecological restoration and site condition improvement.

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