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Growth Rate, Competition, Understory Diversity, and Understory Species Richness in Pure Versus Mixed *Cunninghamia lanceolata* (Lamb.) Hook Ecological Plantations in Guangdong Province, China

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Abstract: This research investigated the growth performance and understory dynamics of Chinese fir (*Cunninghamia lanceolata*) in two ecological plantations 10 km apart in Guangdong Province, China. One ecological plantation was a monoculture comprised solely of Chinese fir. In contrast, the other ecological plantation featured a mix of 30% Chinese fir and 22 other species, encompassing three exotic, five shade-tolerant, six shade-intolerant, and eleven neutral species. Both ecological plantations utilized 1-year-old seedlings planted at 2m × 2m spacing. After 16 years, soil analysis revealed no disparities between the two ecological plantations in total nitrogen, phosphorus, potassium, or pH. Chinese fir in the mixed ecological plantation displayed superior growth, with a 13% increase in diameter, an 18% increase in height, and a 33% increase in crown width compared to those in the monoculture. The leaf area index was higher, and canopy openness was lower in the mixed ecological plantation, indicating an improved canopy structure. Competition indices indicated reduced competition for diameter and increased competition for crown width in the mixed ecological plantation, with no significant difference in competition for height. The monoculture ecological plantation showed higher understory shrub diversity and richness, but no differences were observed in herb diversity and richness between the two ecological plantations. These findings underscore the advantages of mixed-species ecological plantation in enhancing the growth performance of Chinese fir while demonstrating differing effects on shrub and herbaceous understory layers.

Keywords: *Cunninghamia lanceolata*; pure and mixed species ecological plantations; growth rate; competition; understory diversity and species richness

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1. Introduction

The Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook**)** is a rapidly growing native tree species that is prevalent in the southern subtropical regions of China [1,2]. It is the oldest commercial timber species planted in Guangdong province. In 1985, the Guangdong Government launched a plan to "rehabilitating degraded forest land in five years and greening Guangdong in ten years" [3]. By the end of 1993, trees covered 3.33 million hectares of degraded forest lands, resulting in a 57 percent increase in forest cover [3]. However, the forest rehabilitation efforts resulted in extensive monoculture landscapes of Chinese fir, leading to subpar growth and increased susceptibility to pests and diseases [4,5]. The most significant damage was caused by *Bipolaris sacchari* (E. Buther) Shoem, the pathogen responsible for causing Chinese fir shoot blight [6].

In 1994, the Guangdong Government made a significant move by classifying the forests in China's first province as 'commercial' or 'ecological', with a strict no-logging policy in the latter [3,7].

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These ecological forests, covering 3.4 million hectares and constituting approximately 33% of the provincial land, included natural reserves, forest parks, farmland protection forests, water and soil conservation forests, water source protection forests, coastal protection forests, and forests along roads, railways, and reservoirs. This proactive step preserved these ecological forests and provided opportunities to enhance and modernize forestry practices by establishing long-term research plots to study sustainable forest management. A key area of research was the potential benefits of cultivating Chinese fir in species mixtures compared to monocultures.

There is a rising interest in mixed-species plantation systems [8–10] due to their ability to enhance soil fertility [11], mainly when nitrogen-fixing species are involved [12]. These systems also contribute to improved survival rates and greater productivity of species [13,14], reduced damage from pests or diseases [15,16], enhanced biodiversity and wildlife habitats [17,18], increased carbon sequestration [19], better adaptation to climate change and environmental stress [20,21] and economic and risk diversification [22]. However, despite these well-documented benefits and the increasing interest in mixed species plantation systems, the planting areas in the southern subtropical regions of China remain limited. This underscores the urgent need for more research and guidelines for designing and managing mixed-species systems, including the social and ecological factors crucial for successful mixed-species plantings.

Our research compared Chinese fir growth in pure and mixed-species ecological plantations in Guangdong province at the 16-year mark. Our study aimed to address the following two inquiries:

1. Does planting Chinese fir in the mixed-species ecological plantations, as opposed to monoculture, increase overall ecological plantation productivity?

2. Does mixed-species ecological plantation provide more diverse plant fauna than monoculture ecological plantation?

2. Materials and Methods

2.1. Study Sites

This study occurred at two ecological plantations 10 km apart in Guangdong province, China. The ecological plantations consisted of the following:

I. Pure Chinese fir, covering an area totalling 193 hm^2

II. Chinese fir in a mix of 22 species (3 exotica, five shade-tolerant, six shade-intolerant, 11 neutral), covering an area totalling 356 hm^2

The characteristics of the two ecological plantations are detailed in Table 1.

Table 1. Summary of plantation characteristics in pure versus mixed *Cunninghamia lanceolata* in Guangdong province. [1] Mixed *Cunninghamia lanceolata* has 22 species with 30% *Cunninghamia lanceolate*. [2] Sig: Statistical test of significance between pure and mixed plantations; ns is not significant. In brackets are the standard errors.

Plantations[1]	Pure	Mixed	Sig[2]
Geographic			
Latitude (N)	25°11′57.3″	25°10′22.32″	
Longitude (E)	113°27′9.2″	113°18′57.2″	
Elevation (m)	204	227	
Temperature (°C)	19.6	19.6	
Rainfall (mm)	1545.6	1532.7	
Area (hm^2)	193	356	
Soil			
Nitrogen (g/kg)	0.80 (0.29)	1.15 (0.29)	ns
Phosphorus (g/kg)	0.52 (0.25)	0.55 (0.25)	ns
Potassium (g/kg)	20.44 (1.68)	18.27 (1.67)	ns
pH	4.21 (0.06)	4.42 (0.05)	ns
Age (yr)	16	16	

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2.2. Experimental Design

From March to May, one-year-old seedlings were planted in row plots on the two ecological plantations with a 2.0 x 2.0 m spacing. To ensure their survival for the first three years of field growth, the seedlings received fertilization in September and October.

A field assessment was conducted in the fall when the trees were 16, after the cessation of shoot growth. Quadrant plots of 600 m^2 were laid out on the two ecological plantations. The pure Chinese fir ecological plantation had seven quadrant plots, while the mixed Chinese fir ecological plantation had 15. Each 600 m^2 quadrant plot was divided into six 10 m^2 x 10 m^2 subplots.

2.3. Data Sampling

In each 600 m^2 quadrant plot, we measured the height of trees to the nearest meter, the diameter at breast height to the nearest centimeter, and the crown width to the nearest meter. The canopy structure of individual trees was assessed by capturing a hemispherical canopy image using a Nikon Coolpix 4500 digital camera connected to a Nikon FC-E8 fisheye lens, saved with a resolution of 1600 x 1200. We selected shooting points at the center and diagonal points, each representing 10m x 10m quadrats. The camera was positioned 1.6m above the ground at the tree's base, with the lens kept level upward. We took three photos at each point, totalling 15 for a hemispherical canopy image.

In each 10m x 10m quadrat subplot, we positioned a 2m x 2m small quadrant at each of the four corners. Within each 2m x 2m small quadrant, we documented the species composition, individual count, height, and coverage of shrubs and herbaceous plants in the understory. We gathered five soil samples at 20 cm, 40 cm, and 60 cm distances from each 2m x 2m small quadrant. These soil samples were thoroughly mixed, and 1 kg of the composite soil was securely sealed and transported to the laboratory.

2.4. Data Analyses

We have calculated the growth rates for diameter at breast height (GR-D), height (GR-H), and crown width (GR-W), as well as the competition indices for each of these growth rates (CI-D, CI-H, CI-W). The competition index (CI) for each focal tree was determined using the formula

$$CI = \Sigma GDi / N \quad (1)$$

where GDi is the growth rate of the ith neighbour, and N is the total number of neighbours (ranging from 1 to 8). A higher CI indicates a more significant competitive impact from neighbouring trees on the focal tree.

The biodiversity of understory species in each ecological plantation was assessed using the Shannon-Wiener index (H), which is calculated as

$$H = \Sigma(Pi * \ln Pi) \quad (2)$$

where Pi represents the proportion of individuals for each species, and ln denotes the natural logarithm [23]. The Shannon-Wiener index is a widely used ecological metric that measures the diversity of a community. It considers species richness (the number of species present) and species evenness (the relative abundance). A high Shannon-Wiener Index signifies a high level of species diversity, indicating a wide variety of species with individuals evenly distributed among them. Conversely, a low Shannon-Wiener Index indicates lower diversity, which could result from a smaller number of species or an uneven distribution (e.g., a few dominant species). A value of $H = 0$ signifies a community with only one species.

The Margalef index (F) was employed to evaluate the species richness of the understory. This index, calculated as

$$F = (S-1) / \ln N \quad (3)$$

where S is the number of species and N is the total number of individuals in the sample, accounting for the impact of sample size on species richness [23]. Doing so minimizes potential bias resulting from variations in sample size across communities. A higher value of the Margalef Index indicates a greater species richness within a community, signifying the presence of more species relative to the total number of individuals. Conversely, a lower value suggests reduced species richness, indicating either fewer species present or a disproportionately high number of individuals relative to the number of species. It is important to note that the Margalef index does not account for species evenness or the relative abundance of different species within the community. Therefore, it is commonly used in conjunction with other diversity indices to gain a comprehensive understanding of community composition and structure.

At each ecological plantation, we assessed the leaf area index (LAI) and canopy openness (%) using the Gap Light Analyzer Version 2.0 [24,25] to determine the crucial indicators of canopy density and light availability. LAI represents the ratio of total leaf area to ground area, indicating the leaf surface area available to intercept sunlight. Canopy openness, on the other hand, signifies the proportion of sky visible through the canopy, affecting the amount of light reaching the understory.

These factors, LAI and canopy openness, significantly impact light availability, water retention, and nutrient dynamics, which are critical for plant productivity and diversity [26,27].

The degree of canopy openness and LAI are interconnected factors that jointly regulate the quantity of light reaching the lower levels of vegetation. A dense canopy characterized by a high LAI can effectively restrict light penetration, thereby influencing the amount of light reaching the lower levels of vegetation. In contrast, openings in the canopy, reflected in the canopy openness, enable intermittent influxes of light. These openings can promote the growth of understory vegetation by allowing more light to reach the lower levels of vegetation. Therefore, the relationship between LAI and canopy openness is a critical factor in understanding the combined impact of these factors on vegetation growth.

In addition, we analyzed the soil samples for total nitrogen, total phosphorus, total potassium, and pH using specific methods:

- Total nitrogen: Half-Micro Kjeldahl titration method [28].
- Total phosphorus: Sodium hydroxide alkali melting-molybdenum blue colorimetric method [29].
- Total potassium: Sodium hydroxide melting-flame spectrophotometry [30].

2.5. Statistical Analysis

We utilized the Independent Samples t-test in SPSS [31] to compare the means of pure Chinese fir ecological plantation and mixed-species Chinese fir ecological plantation. This allowed us to determine whether the two had a significant difference. A p-value below 0.05 would indicate that the Chinese fir ecological plantation means differed significantly, showing statistical significance.

3. Results

3.1. Study Sites

The absence of significant differences in total nitrogen, phosphorus, potassium, and pH in Table 1 suggests that both plantations have reached similar nutrient conditions after 16 years. This could indicate that plant-soil feedback processes have mitigated any initial variation [32,33]**.** Thus, structural and ecological interactions in these two ecological plantations were more likely to drive growth differences than differences in soil fertility.

3.2. Growth Rate

The data in Table 2 shows the mean diameter growth rate (GR-D), height growth rate (GR-H), and crown width growth rate (GR-W) for two ecological plantations. In the pure Chinese fir ecological plantation, the GR-D, GR-H, and GR-W were 0.91 ± 0.05, 0.67 ± 0.03, and 0.18 ± 0.02, respectively. In the mixed Chinese fir ecological plantation, the growth rates were higher, with GR-D at 1.03 ± 0.02, GR-H at 0.79 ± 0.02, and GR-W at 0.24 ± 0.01, representing increases of 13%, 18%, and

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33% respectively. Statistical analysis revealed significant differences in GR-D, GR-H, and GR-W between the pure and mixed Chinese fir ecological plantations.

Table 2. Growth rate, competition and canopy structure of *Cunninghamia lanceolata* in pure and mixed plantations in Guangdong province. [1] Mixed *Cunninghamia lanceolata* has 22 species with 30% *Cunninghamia lanceolate*. [2] Sig: Statistical test of significance between pure and mixed plantations, ns is not significant. [3] GR-D: Diameter at breast height growth rate (cm/yr); GR-H: Height growth rate (m/yr); GR-W: Crown width growth rate (m/yr). [4] CI-D: Competition index of GR-D; CI-H: Competition index of GR-H; CI-W: Competition index of GR-W. In brackets are the standard errors.

Plantations[1]	Pure	Mixed	Sig[2]
Growth Rate[3]			
GR-D	0.91 (0.05)	1.03 (0.02)	0.03
GR-H	0.67 (0.03)	0.79 (0.04)	0.02
GR-W	0.18 (0.02)	0.24 (0.01)	0.02
Competition[4]			
CI-D	9.06 (0.13)	8.20 (0.20)	0.05
CI-H	6.61 (0.09)	6.66 (0.15)	ns
CI-W	1.77 (0.08)	2.67 (0.06)	0.00
Canopy Structure			
LAI)	2.03 (0.12)	2.67 (0.06)	0.02
Canopy Openness	16.78 (1.20)	13.61 (0.51)	0.01

3.3. Competition

Table 2 provides the competition index of diameter growth rate (CI-D), competition index of height growth rate (CI-H), and competition index of crown width growth rate (CI-W) for Chinese fir in two different ecological plantations. In the pure Chinese fir ecological plantation, the CI-D, CI-H, and CI-W were recorded as 9.06 ± 0.13, 6.61 ± 0.09, and 1.77 ± 0.08, respectively. In comparison, the CI-D for Chinese fir in the mixed Chinese fir ecological plantation was 8.20 ± 0.20, which was significantly lower (by 9.5%). The CI-H for the Chinese fir in the mixed Chinese fir ecological plantation was 6.66 ± 0.09, showing no significant difference from that of the pure Chinese fir ecological plantation. However, the CI-W for Chinese fir in the mixed Chinese fir ecological plantation was 2.67 ± 0.06, significantly higher (by 51%) than that of Chinese fir growing in the pure Chinese ecological plantation.

3.4. Canopy Structure

The leaf area index (LAI) of Chinese fir in the pure Chinese fir ecological plantation was 2.03 ± 0.12, which was significantly smaller (32%) than the LAI of Chinese fir in the mixed Chinese fir ecological plantation, measuring 2.67 ± 0.06 (Table 2). Furthermore, the canopy openness (%) of Chinese fir in the pure Chinese fir ecological plantation was 16.78 ± 1.20, significantly greater (19%) than that of Chinese fir in the mixed Chinese fir ecological plantation, which was 13.61 ± 0.51 (Table 2).

3.5. Understory Diversity and Species Richness

A detailed comparison of understory diversity and species richness between two ecological plantations is presented in Table 3. The shrub Shannon-Wiener index (H) of the pure Chinese fir ecological plantation, at 1.97 ± 0.14, showed statistically significant differences compared to the 1.59 ± 0.08 value of the mixed Chinese fir ecological plantation. However, the herb H of the pure Chinese fir ecological plantation, at 0.85 ± 0.18, did not exhibit a significant difference from the 0.92 ± 0.10 herb H of the mixed Chinese fir ecological plantation. Additionally, the shrub Margalef index (F) of the pure Chinese fir ecological plantation, at 3.08 ± 0.35, was significantly greater than the 2.27 ± 0.13 value observed for the mixed Chinese fir ecological plantation. On the other hand, the herb F of the

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pure Chinese fir ecological plantation, at 1.00 ± 0.21, did not show a significant difference from the 1.60 ± 0.35 herb *F* of the mixed Chinese fir ecological plantation.

Table 3. Understory diversity and understory species richness in pure versus mixed *Cunninghamia lanceolata* plantations in Guangdong province. [1] Mixed *Cunninghamia lanceolata* has 22 species with 30% *Cunninghamia lanceolate*. [2] Sig: Statistical test of significance between pure and mixed plantations, ns is not significant. [3] H: Shannon-Wiener index. [4] F: Margalef index. In brackets are the standard errors.

Plantations[1]	Pure	Mixed	Sig[2]
Understory Diversity			
Shrub *H*	1.97 (0.14)	1.59 (0.08)	0.02
Herb *H*	0.85 (0.19)	0.92 (0.10)	ns
Understory Species Richness[4]			
Shrub *F*	3.08 (0.35)	2.27 (0.13)	0.01
Herb *F*	1.00 (0.21)	1.60 (0.35)	ns

4. Discussion

The Chinese fir is a rapidly growing and economically significant conifer extensively cultivated in southern China. Although monoculture plantations of Chinese fir have been favored for their timber productivity, these plantations face a significant challenge in soil degradation, particularly the depletion of essential nutrients. Repeated planting of a single species like Chinese fir often depletes vital nutrients, especially nitrogen and phosphorus [34], causing a decline in productivity over successive rotations [35]. On the other hand, incorporating Chinese fir with multiple tree species has improved nutrient cycling by introducing diverse organic matter into the soil, enriching it with nutrients beneficial to all species in the plantation [36,37]. This approach can contribute to the site's long-term sustainability and improve soil health over time.

Our study comparing pure and mixed-species Chinese fir plantations revealed significant ecological and structural differences, particularly in leaf area index, canopy openness, growth patterns, competition indices, and understory diversity. These results are consistent with research on forest management strategies emphasizing mixed-species systems' advantages. Below, we interpret the ecological mechanisms underlying our key findings and their broader implications.

4.1. Productivity

Our research revealed that the growth rate of Chinese fir in the mixed ecological plantation significantly outperformed that in the pure ecological plantation. Specifically, we observed a 13% increase in diameter, an 18% increase in height, and a 33% increase in crown width for the Chinese fir in the mixed plantation compared to those in the pure plantation (see Table 2). Additionally, the Chinese fir in the mixed-species ecological plantation displayed a smaller competition index for diameter, a greater competition index for crown width, and no significant difference in the competition index for height compared to those in the pure Chinese fir ecological plantation. The differences in growth rate and competition indices between the two ecological plantations could stem from **better resource-use efficiency and reduced intra-specific competition** in the mixed plantation. However, the mixed-species environment presented **greater competition for crown width** due to more diverse canopy structures, demonstrating the trade-off between **above-ground and below-ground resource competition [38,39]**. These findings support the benefits of **mixed-species plantations** in enhancing growth and sustainability compared to monocultures[40,41], particularly for species like Chinese fir [42].

In our mixed-species Chinese fir ecological plantation, the presence of different species with complementary root architectures and nutrient requirements would mitigate intraspecific competition and improve resource acquisition [43]. For instance, Chinese fir could benefit from species with deeper root systems that access different soil horizons, resulting in more efficient use of

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nutrients, water, and sunlight [44,45]. Conversely, in the pure Chinese fir ecological plantation, intense intraspecific competition was observed due to the similarity in ecological niches and growth habits among all Chinese fir trees. In contrast, mixed-species plantations showed reduced competition among Chinese fir trees, particularly for resources such as light and soil nutrients. This could be attributed to species occupying different canopy levels or having varying growth rates [46,47], shedding light on why Chinese fir demonstrated higher growth in the mixed Chinese fir ecological plantation than in the pure ecological plantation.

Integrating a mixed-species Chinese fir ecological plantation is anticipated to improve soil structure and nutrient availability, especially when incorporating broadleaf species. These species contribute a more significant amount of organic matter through leaf litter decomposition [48], thereby fostering enhanced root growth and overall tree health. This enhancement is reflected in the trees' increased diameter and crown width.

The competition index for trunk diameter was lower in mixed-species Chinese fir ecological plantations. This is likely due to a decrease in direct competition for trunk expansion. Chinese fir trees compete for similar horizontal space to expand their trunks in monocultures. However, in mixed plantations, different species occupy distinct niches, providing more space for Chinese fir to expand its trunk with less competition from neighboring trees, as demonstrated in the case of European beech (*Fagus sylvatica* L.) [49]. The structural diversity of Chinese fir in mixed-species ecological plantations means that neighbouring species are less likely to crowd each other out at the same horizontal level, allowing for more substantial diameter growth in Chinese fir.

In mixed-species plantations, the competition index for crown width is likely higher due to increased competition for lateral crown expansion. Fast-growing, broadleaf species in the ecological plantation take up more horizontal space in the canopy than conifers like Chinese fir. Consequently, broadleaf trees cast more comprehensive shadows and occupy more lateral space, intensifying the competition for canopy space in the upper layers. This results in a greater competition index for crown width, with Chinese fir facing significant competition from broadleaf species for lateral canopy growth [50]. In contrast, in a pure Chinese fir ecological plantation, competition for crown width might be more balanced, as all trees would have similar crown structures and occupy the same vertical and horizontal space.

4.2. Diversity

In the pure Chinese fir ecological plantation, there was a higher diversity and species richness of understory shrubs compared to the mixed plantation. However, there were no significant differences in the diversity and species richness of understory herbs between the two ecological plantations (refer to Table 3). The increased diversity and richness of understory shrubs in the pure plantation could be attributed to the greater canopy openness, allowing more light to promote shrub growth, as shrubs typically thrive in well-lit environments (see Table 2). Conversely, in the mixed plantation, the lower canopy openness might hinder shrub growth, resulting in limited light reaching the understory. The absence of variation in herb diversity and richness suggests that herbs might be more adaptable to shade or respond similarly in both Chinese fir ecological plantations [51–53].

5. Conclusion

This study demonstrates that mixed-species plantations of Chinese fir could significantly enhance growth by improving resource use efficiency and reducing intraspecific competition, though they also increased above-ground competition for lateral crown space. The trade-offs between productivity and biodiversity were evident in the differences in understory shrub diversity and richness, which were higher in the pure Chinese fir ecological plantation due to greater canopy openness. However, herbaceous species richness remained stable across both Chinese fir ecological plantation types, underscoring their adaptability to varied light conditions. Despite no discernible difference in soil nutrients between the two ecological plantations, the structural and ecological complexity of the mixed species ecological plantation they have resulted in better growth outcomes for Chinese fir.

The study was conducted at two plantation sites 10 km apart within a specific geographic region (Guangdong province) and focused on a single time point (16 years after planting). Additionally, the mixed-species ecological plantation comprised a unique combination of 22 species, and the mix of these species might have impacted the results, as different combinations could yield different results. Therefore, broader generalizations may need to be validated across diverse climates and soil types in the long term, going beyond the scope of this study. Despite these constraints, this study adds to the mounting evidence suggesting that mixed-species plantations surpass monocultures in various aspects, fostering growth and ecological sustainability.

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