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Assessing the Relationship between Tree Growth, Crown Size, and Neighboring Tree Species Diversity in Mixed Coniferous and Broad Forests Using Crown Size Competition Indices

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Abstract: Competition among trees for limited resources (e.g., sunlight, water, and nutrients) impacts their growth differently. Crown plays a crucial role in resource access for trees. However, uncertainties persist regarding crown size differences, tree growth, and tree competition levels between coniferous and broadleaf trees in mixed-age forests. We conducted a study on 3008 live trees across 28 plots in Hunan Province to measure individual crown size and tree growth increment. Introducing a new metric, the Crown Size Competition Index (CSCI), we assessed competition pressure among coniferous and broadleaf species in mixed-age forests. We examined the correlation between competition indices and tree growth increment while also investigating the influence of neighboring species diversity on tree competition. Our results revealed a significant negative correlation between the tree growth of *Cunninghamia lanceolata* (Lamb.) Hook. (*CL*) and *Phoebe bournei* (Hemsl.) Yang (*PB*) and the competition index. Increased competitive pressure on the focal tree corresponded to a decline in the growth of focal tree volume, with a more pronounced impact observed in *PB* compared to *CL*. The diversity of neighboring species contributed to variations in competition for the focal tree, with broadleaved species (*PB*) exerting a greater influence on the focal tree than coniferous species (*CL*). These findings underscore the competitive potential of *PB* in mature coniferous stands and advocate for the restoration of stratified mixes in *CL* broadleaf forests. Furthermore, our findings support the management strategies for the valuable tree species *PB*.

Keywords: crown size; neighborhood effects; competition index; tree species diversity; tree growth

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1. Introduction

The interaction among species is a focal point in ecological research, often examined through neighborhood effects [1]. These effects encapsulate the influences on tree growth and development stemming from their immediate surroundings. Individual growth hinges on effective space, influenced by proximity to neighboring trees [2], with denser neighborhoods exerting a more pronounced impact [3,4]. Crown competition is a pivotal aspect of neighborhood effects, where trees vie for light and nutrients through their crowns [5–8], significantly impacting growth and survival [9–11]. The crown of a tree reflects not only its competition but also determines the area available for photosynthesis, thus influencing stand productivity. Crown structure, encompassing size, shape, and relative position within a stand, is pivotal to forest ecology, shaping the dynamic growth of plant communities [12]. Neighborhood effects can be assessed through metrics such as stand density, distance, species composition, and tree height [13], with density and distance being critical determinants influencing crown competition, especially in closer proximity [14]. Species composition also plays a significant role, with varying growth rates and crown sizes among different species [15], some of which are more susceptible to competition due to denser crowns [16].

Tree competition is a fundamental aspect of forest ecology, wherein trees within the same environment compete for essential resources such as sunlight, water, and nutrients crucial for growth and development [17]. This competition results in a reduction in available resources due to neighboring trees, hindering the normal growth and development of others. Throughout forest growth stages, trees mutually influence and impede each other, leading to noticeable differences in individual plant growth [18,19]. Neighboring trees primarily engage in competition within forests, influencing the growth, morphology, and survival of trees [20,21]. The competitive ability of a tree is influenced by factors including tree size, tree developmental stage, growth rate, viability, soil conditions, and surrounding trees [22,23]. This relationship between the focal tree and its neighbors is vital for understanding competition dynamics, contributing to the comprehension of forest development and succession processes. Understanding tree competition aids in predicting forest succession trends and implementing necessary management measures to enhance forest ecosystem functionality and improvement.

Competition among trees is a critical aspect of forest ecology, commonly analyzed through competition indices [24–27]. These indices serve as quantitative indicators, delineating the intensity of tree competition [28–30], influenced by both stand characteristics (such as diameter at breast height (DBH), tree height, crown size) and environmental factors [31–33]. Two major categories of competition models exist: distance-related and distance-independent [34]. Distance-independent models include stand size ratio and stem height ratio, while distance-related models encompass crown overlap, point density, and growing space. In 1974, Hegyi introduced a competition index based on DBH ratio and distance between competing trees [35]. However, trees with similar DBH often exhibit significant differences in crown size, particularly between conifers and broadleaf trees [36]. Since crown size correlates closely with a tree's ability to acquire growth resources, competition index models considering crown characteristics are more appropriate for expressing competitive pressure [37]. The primary challenge in competition index research lies in quantifying the impact of tree competition on tree growth. Competing trees noticeably affect forest growth, influencing changes in stand structure [38–40]. Understanding the role of competition in stand structure is crucial for establishing sustainable forest management practices. However, existing studies often focus on the impact of competition on growth and yield in stands, with limited emphasis on individual tree responses.

Cunninghamia lanceolata (Lamb.) Hook. (*CL*) forests cover the largest area in southern China as the pure forest type. Transitioning these pure *CL* forests into mixed forests using near-natural management techniques is pivotal for enhancing their ecological functions. In these pure coniferous *CL* forests, rare broadleaved species such as *Phoebe bournei* (Hemsl.) Yang (*PB*) are being artificially reintroduced. This initiative not only promotes *CL* plantation growth but also aids in the cultivation of the rare and valuable *PB* tree species [41]. Studies indicate that mixed forests of *Cunninghamia lanceolata* and *Phoebe bournei* (*CLPB*) offer greater timber production and enhanced ecological benefits compared to pure *CL* forests [42]. Understanding potential differences in competition between coniferous and broadleaved trees within mixed forests, and how neighboring tree identity influences competition for the focal tree, is crucial for a comprehensive grasp of forest dynamics and the implementation of effective management practices.

A thorough comprehension of competition effects on *CLPB* at the neighborhood level is essential for a comprehensive assessment of the benefits of structurally complex, mixed-species stands in forest management. This study aims to analyze the relationship between crown size, tree growth increment, and competition intensity in *CLPB* mixed forests, investigating the impacts of tree competition and neighboring species on tree growth increment. To quantify crown competition effects, we employed a crown size competition index. In this paper, we address the following key questions. (1) Do *CL* and *PB* exhibit differences in crown size and competitive intensity? (2) What is the correlation between tree growth increment and tree competition indices? Our hypothesis posits that an increase in competition intensity from neighboring trees against *CL* and *PB* would result in reduced stem volume growth, with a more pronounced effect on *PB* than on *CL*. (3) Do the species of neighboring trees lead to differences in the size of competition for focal tree? Our hypothesis suggests that broadleaved species (*PB*) would exert a greater effect than coniferous species (*CL*) on the focal tree.

2. Materials and Methods

2.1. Study Area

The study was conducted at Jindong Forest Farm, situated in the southern part of Qiyang County, Hunan Province, China (Figure 1). Positioned in the middle and upper reaches of the Xiangjiang River Basin, the farm features dense mountains and steep slopes, with an average slope of 34° and 95.2% of terrain classified as grade IV and above (26° or above). The highest altitude is 1435 m, and the lowest is 108 m. The forest farm's soil primarily consists of yellow-red and yellow soils, typically with a soil layer thickness exceeding 60 cm. Gravel content ranges from 20% to 30%, and the average soil organic matter content exceeds 2%, reaching a maximum value of 11%. The region falls within the subtropical southeast monsoon humid climate zone, characterized by an average annual temperature of 18 °C. Extreme temperatures include a maximum of 41 °C and a minimum of −8 °C. The average annual effective sunshine duration is 1617 h, annual precipitation ranges from 1600 to 1890 mm, and average annual evaporation is 1225 mm. Relative humidity hovers between 75 and 82%, the annual frost-free period spans 265–349 days, and the vegetation experiences 281–301 natural days. The forest cover of the forest farm is 98.48% [43].

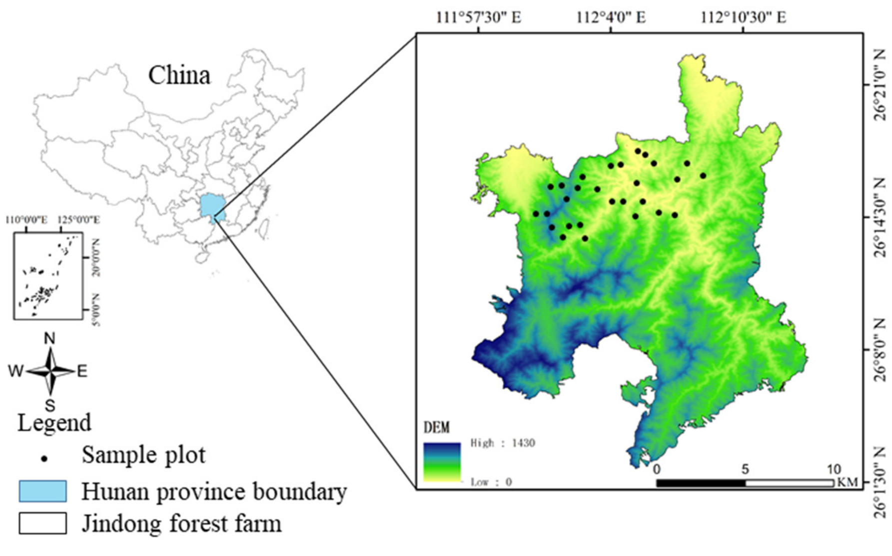

Figure 1. Location of the study site.

2.2. Study Design and Sampling

A standardized plot measuring 20 m × 30 m was established within the *CLPB* mixed forest stand (*CL* and *PB* are the same age), with a total of 28 sample plots (comprising 4012 trees) set up in 2023. The survey specifically targeted all trees within the sample plots whose diameter at breast height (DBH) reached or exceeded the initial diameter step of 5 cm, and each tree was assigned a unique identifier. The survey encompassed key parameters such as tree species, DBH, tree height, crown width, under-branch height, and tree coordinates (X, Y).

2.3. Crown Measurement

For crown measurements, the compass and long pole need to be utilized. To enhance the accuracy of crown size measurements and minimize estimation errors, we recommend the following procedure. Initially, one person should stand facing the tree in a specific compass direction, holding a vertically erected long pole in front of them. Subsequently, another person should position themselves at a certain distance perpendicular to the first person, facing one of their shoulders. This person will then guide the first person forward or backward until the pole can be precisely pointed at the furthest extension of the visible lateral branch. Lastly, measure the distance from the trunk to the bottom of the pole. Repeat this process for the other three compass directions. Adhering to this method helps minimize estimation errors and ensures a more accurate measurement of the tree's dimensions.

By employing this approach to estimate crown projection, it ensures that the resulting crown shape will be a closed-angle polygon (Figure 2), a prerequisite for the geometrical analysis employed. However, it is crucial to acknowledge that for trees with irregular crowns, this method may lead to an overestimation of the canopy projection. Furthermore, it is important to clarify that the distance between the trunk and the edge of the polygon solely signifies the spread of the crown, not the length of the branches. Additionally, it should be emphasized that estimates of the maximum and minimum lateral extensions for a tree are susceptible to a certain degree of error, as they are based solely on measurements taken in four compass directions.

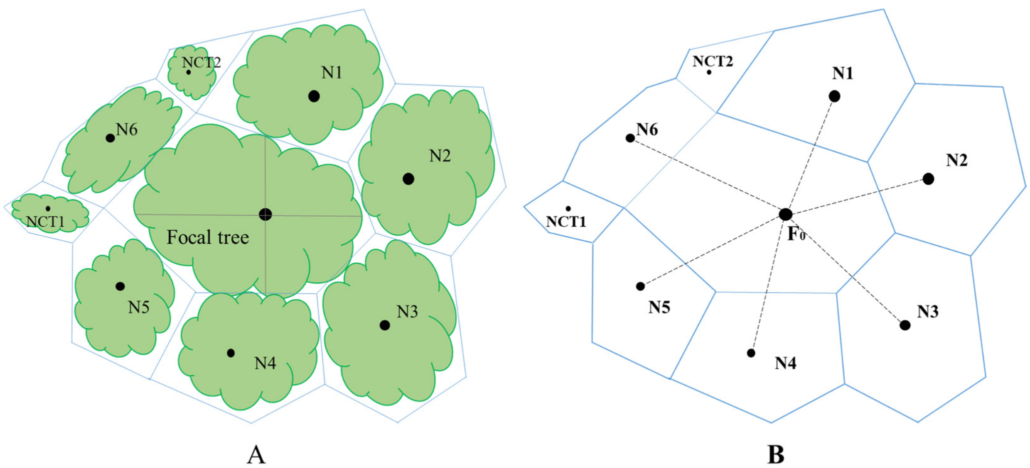

Figure 2. Vertical crown projection and competitive pressure from neighbors. (**A**) The solid circle is the location of the stem. N1, N2, N3, N4, N5, N6 are Neighbor tree 1, Neighbor tree 2, Neighbor tree 3, Neighbor tree 4, Neighbor tree 5, Neighbor tree 6. NCT is Non-competing tree. The two vertical lines of the core tree represent the length of the crown. (**B**) Crown polygon with location of stem (F0), where the dashed line is the distance between the focal tree and neighboring tree.

2.4. Statistical Analysis

2.4.1. Competition Index

The simple competition index proposed by Hegyi (1974) utilizes the ratio of the competing tree to the focal tree, along with the ratio of the distances between the two trees [35]. The index is calculated using the following equation:

$$CI_i = \sum_{j=1}^{N} \frac{D_j}{D_i} \times \frac{1}{L_{ij}} \quad (1)$$

where CI_i is the Hegyi competition index of focal tree i; D_i is the DBH of focal tree i; D_j is the DBH of competitor j (j = 1, 2, 3, . . . , N); L_{ij} is the distance between focal tree i and competitor tree j. In this study, we used the four-tree method to identify neighboring trees [44].

According to the Hegyi competition index, Zhang et al. [45] incorporated the crown factor into the assessment and computation of forest tree competition, designating any of the focal trees whose crown overlaps with the trees as competing trees. In this study, the crown length ratio of tree crowns was integrated into the crown competition index. The competition index is divided into two components. The first part represents competition in the vertical direction, considering the ratio of the crown length of the competing tree to the height of the tree (i.e., crown length ratio) compared to the crown length ratio of the focal tree, capturing the effect of crown shading in the vertical direction. The second part represents competition in the horizontal direction, characterized by the degree of mutual shading between the crowns of the competing tree and the focal tree in the horizontal plane. This is defined by the ratio of the overlapping part of the crowns of the competing tree and the focal tree to the crown length ratio of the focal tree. The intensity of competition in the horizontal direction of the stand is expressed by introducing a factor: the ratio of the overlapping part of the crown of the competing and focal trees to the radius of the crown of the focal tree. Following mathematical principles, the formula is as follows:

$$CSCI_i = \sum_{j=1}^{N} \frac{\left(H_j - Hb_j\right) H_i}{H_j (H_i - Hb_i)} \times \frac{\left| Cr_i + Cr_j - \left| X_i - X_j \right| \right|}{Cr_i} \quad (2)$$

where $CSCI_i$ is the crown size competition index, H_i is the height of the focal tree, Hb_i is the under-branch height of the focal tree, H_j is the height of the competing tree judged by using Formula (1), Hb_j is the under-branch height of the competing tree, Cr_i is the crown radius of the focal tree, Cr_j is the crown radius of the competing tree, and $\left| X_i - X_j \right|$ is the distance between the focal tree and the competing tree. The neighboring trees were selected using ArcGis10.7 software.

The CSCI (crown size competition index) is directly correlated with the size of the tree's crown; larger canopies correspond to greater competition. In previous perspectives on competing trees, close neighboring trees were considered competing trees. However, according to the CSCI defined in this study, close neighboring trees may not necessarily be competing trees. For a specific focal tree, both its crown and the crowns of neighboring trees undergo dynamic changes. Consequently, the competition intensity of the focal tree is also dynamic, and the number of competing trees is subject to change. Monitoring and calculating how far away from the focal tree a tree can be considered a competing tree need to be performed dynamically over the long term.

2.4.2. Diversity Variable

To date, there exist various methods for representing tree species diversity [46]. The species diversity index by Fisher et al. [47] solely measures species richness, lacking the capability to assess the distribution of species among different species. The segregation index introduced by Pielou [48] is applicable only for two-by-two comparisons of tree species. Subsequently, Gadow et al. [49] proposed the concept of hybridity. Hybridity is defined as the proportion of individuals in the n nearest neighbors of the focal tree i that differ in species from the focal tree. It is expressed by the following formula:

$$M_i = \frac{1}{n} \sum_{j=1}^{n} v_{ij} \quad (3)$$

where M_i is the mingling degree of focal tree i, n is the number of neighboring trees of focal tree i, v_{ij} is a discrete variable, when the neighboring tree j is of a different species from focal tree i, v_{ij} = 1; otherwise, v_{ij} = 0.

2.4.3. Annual Growth Increment

Tree growth refers to the changes that occur in various survey factors of trees over a certain interval, and the amount of change is the increment. Annual growth increment (Z)

is the amount of growth of a tree in one year. In this study, the annual growth increment in *DBH*, tree height, and stem volume are used to indicate the amount of growth changes in *DBH*, tree height, and stem volume. The formula is:

$$Z_H = H_t - H_{t-1} \quad (4)$$

$$Z_{DBH} = DBH_t - DBH_{t-1} \quad (5)$$

$$Z_V = V_t - V_{t-1} \quad (6)$$

where Z_H is the annual growth increment in height, Z_{DBH} is the annual growth increment in *DBH*, Z_V is the annual growth increment in stem volume, H_t is the tree height at t year, H_{t-1} is the tree height at $t-1$ year, DBH_t is the DBH at t year,DBH_{t-1} is the DBH at $t-1$ year.V_t is the stem volume at t year, while V_{t-1} is the stem volume at $t-1$ year.

2.4.4. Inverse Distance Weighting

Inverse Distance Weighting (IDW) interpolation is a distance-based spatial interpolation method. It assumes that the value of an unknown point is directly proportional to the values of surrounding known points but inversely proportional to the power of their distances. In other words, closer known points have a greater influence on the estimation of the unknown point's value, while farther known points have less influence. By calculating the distances between the unknown point and all known points, and then weighting these distances by their inverse powers, the IDW method computes a weighted average of the values of known points to estimate the value of the unknown point. This allows for the estimation of unknown point values based on the observed values of known points and their distances from the unknown point, thereby achieving interpolation of the unknown points. The calculation formula is as follows:

$$Z(u) = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \quad (7)$$

where $Z(u)$ is the estimated value at the unmeasured location, Z_i is the measured value at each known location, d_i is the distance between the unmeasured location and each known location, p is a power parameter that controls the rate at which the influence of measured values decreases with distance. In this study, ArcGis 10.7 software was used to produce IDW difference maps.

3. Results

3.1. Spatial Distribution of Crown Size and Competition Index

In this exemplary survey, a total of 3008 living trees were retained after edge-correction of the sample plots. Among them were 1719 *CL*, 1171 *PB*, 58 *CC*, 43 *SS*, and a few other broadleaf species, totaling 17 different species. The characteristics of the trees in the sample plots are presented in Table 1. In the *CLPB* mixed forest, *CL* exhibits slightly larger dimensions than *PB* in terms of DBH, height, under-branch height, and crown length, but is slightly smaller in crown width.

Table 1. The information of tree size in sample plots.

Specise	Number of Trees	Average DBH (cm)	Average H (m)	Average CW (m)	Average CL (m)	Average UBH (m)
CL	1719	13.12 (5.0–27.3)	9.40 (3.1–17.3)	2.43 (0.2–6.6)	6.24 (0.2–13.8)	3.79 (0.3–10.3)
PB	1171	9.60 (5.0–22.5)	8.70 (2.0–16.6)	2.48 (0.4–5.6)	5.77 (0.2–12.8)	2.59 (0.2–8.2)
CC	58	10.38 (5.0–25.5)	8.30 (4.1–13.4)	2.29 (0.6–4.5)	5.85 (2.2–10.8)	2.71 (0.8–6.5)
SS	43	8.89 (5.0–16.2)	8.20 (5.3–10.4)	2.28 (0.8–3.4)	6.06 (4.6–8.6)	2.12 (0.7–3.8)
Other broadleaf	17	7.99 (5.2–12.0)	6.50 (1.8–9.8)	2.61 (0.5–5.6)	4.60 (1.3–6.1)	1.91 (0.5–3.9)

DBH: diameter at breast height (cm); H: height (m); CW: crown width (m); CL: crown length (m); UBH: under-branch height; *CL*: *Cunninghamia lanceolata*; *PB*: *Phoebe bournei*; CC: *Cinnamomum camphora*; *SS*: *Schima superba*.

From Figure 3, we can conclude that the crown width of *CL* is predominantly distributed between 1.0 and 4.0 m, while the crown length is distributed between 1.5 and 10.5 m. The crown width of *PB* is mainly distributed between 1 and 4 m, with the crown length ranging between 2 and 10 m. Figure 3 illustrates the trend of crown size for *CL* and *PB*. In terms of the crown shape of *CL*, the overall crown length is larger than the width, and the ratio of crown length to width (1.3076, i.e., slope k) for *CL* is greater than that of *PB* (0.8907).

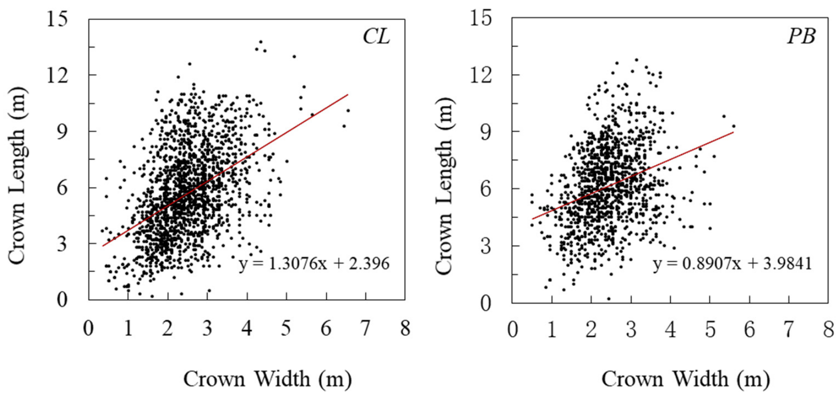

Figure 3. Crown size distribution of single trees of *CL* and *PB*. *CL* denotes *Cunninghamia lanceolata* and *PB* denotes *Phoebe bournei*.

We illustrated the spatial distribution of crown sizes of the trees in the sample plots (Figure 4) (using one of the sample plots as an example). From this, we observed the spatial arrangement of individual trees and the distribution of crowns among them. The analysis (Table 2) revealed that 4.39% of the trees had relatively independent crowns that did not intersect with the crowns of surrounding trees. Additionally, 3.51% of trees had crowns intersecting with one surrounding tree, 17.54% with two surrounding trees, 12.28% with three surrounding trees, and 22.81% with four surrounding trees. Moreover, 17.54% of trees had crowns intersecting with the crowns of five surrounding trees, while 10.53% of trees had crowns intersecting with six surrounding trees. Additionally, 7.89% of trees had their crowns intersecting with seven surrounding trees, and 3.51% of trees had crowns intersecting with eight surrounding trees.

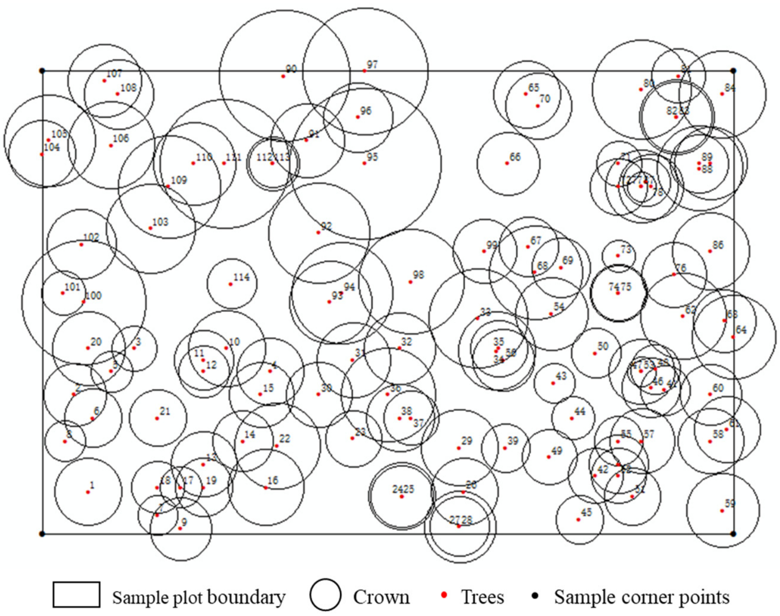

Figure 4. Spatial distribution of crowns of single trees (different-sized circles represent trees with different crown sizes) (an example of a plot).

Table 2. The distribution of neighboring trees around focal trees.

The Number of Neighboring Trees	The Number of Corresponding Focal Trees	Proportion (%)
0	5	4.39
1	4	3.51
2	20	17.54
3	14	12.28
4	26	22.81
5	20	17.54
6	12	10.53
7	9	7.89
8	4	3.51

We utilized the Hegyi CI and the CSCI model to calculate the competition index values for each tree. As shown in Table 3, for *CL*, the average Hegyi CI is 3.99, with a maximum value of 26.58 and a minimum value of 0.76. The average CSCI is 4.03, with a maximum value of 15.18 and a minimum value of 0.00. For *PB*, the average Hegyi CI is 5.09, with a maximum value of 21.53 and a minimum value of 1.17. The average CSCI is 4.69, with a maximum value of 15.24 and a minimum value of 0.00. Subsequently, we employed the Inverse Distance Weighting (IDW) method to interpolate the competition index, generating spatial distribution maps of competition indices within the stand (Figure 5). Regarding the Hegyi CI (Figure 5a), the majority of competition index values fall within the range of 0.76–3.63, accounting for 76.32% of all trees, with a secondary distribution between 3.64 and 6.50, accounting for 14.04% of all trees. As for the CSCI (Figure 5b), competition index values are primarily distributed between 1.70 and 3.37, representing 39.47% of all trees, followed by 0.00–1.69 and 3.38–5.06, each accounting for 22.81% of all trees.

Table 3. The values of Hegyi CI and CSCI for different species.

Tree Species	Hegyi CI				CSCI			
	Mean	SD	Max	Min	Mean	SD	Max	Min
CL	3.99	25.93	26.58	0.76	4.03	13.47	15.18	0.00
PB	5.09	23.17	21.53	1.17	4.69	11.45	15.24	0.00

CL: Cunninghamia lanceolata; PB: Phoebe bournei; Hegyi CI: Hegyi Competition Index; CSCI: Crown Size Competition Index.

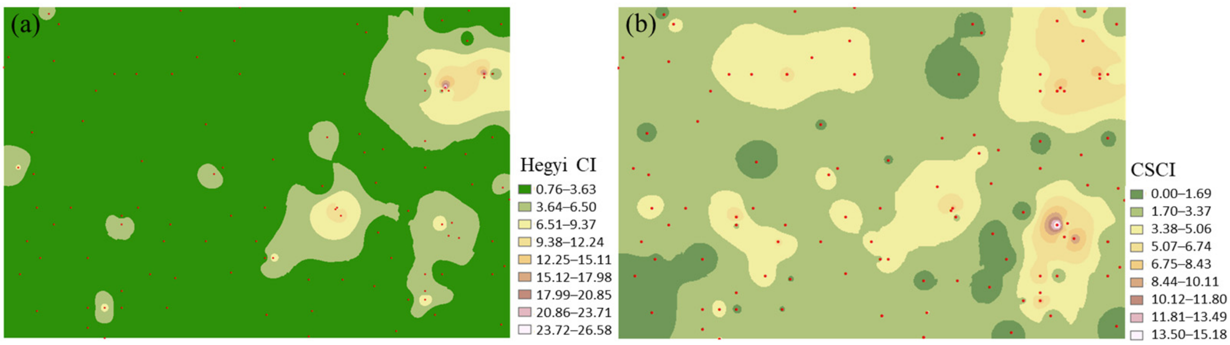

Figure 5. Interpolation figures of IDW for Hegyi CI and CSCI. (**a**) is the interpolation of Hegyi Competition Index and (**b**) is the interpolation of Crown Size Competition Index.

3.2. The Correlation between Tree Growth Increment and Competition Index in CLPB Mixed Forests

We analyzed Pearson's correlation coefficients between annual growth increments (Z) in DBH and tree height and crown size (crown width and crown length), the Hegyi Competition Index (Hegyi CI), and the Crown Size Competition Index (CSCI) for *CL* and *PB* (Table 4). Scatter plots depicting crown width, crown length, CSCI, and Hegyi CI were generated against the annual growth increment in DBH and tree height (Figure 6). The amount of growth was expressed as the annual growth increment in measured tree DBH and tree height. In Figure 6a,b,e,f,i,j,m,n, it is evident that the crown width and crown length sizes of *CL* and *PB* are significantly correlated with the annual growth increment in DBH and tree height, showing an increasing trend in tree growth with larger crown sizes. Both the CSCI and Hegyi CI exhibited significant correlation with tree growth (Figure 6e,d,g,h,k,l,o,p), and the overall correlation trend remained consistent. As the competition index increased, the competitive pressure on the focal tree increased, leading to a decrease in the annual growth increment in DBH and tree height. Analyzing the relationship between changes in tree growth and the competition index suggests that the substantial crown size of *CL* and *PB* after stand depression leads to increased absorption of nutrients and light, thereby promoting stand growth. Conversely, excessive competition within the stand inhibits overall growth, while a reduction in crown crowding and competition enhances stand growth.

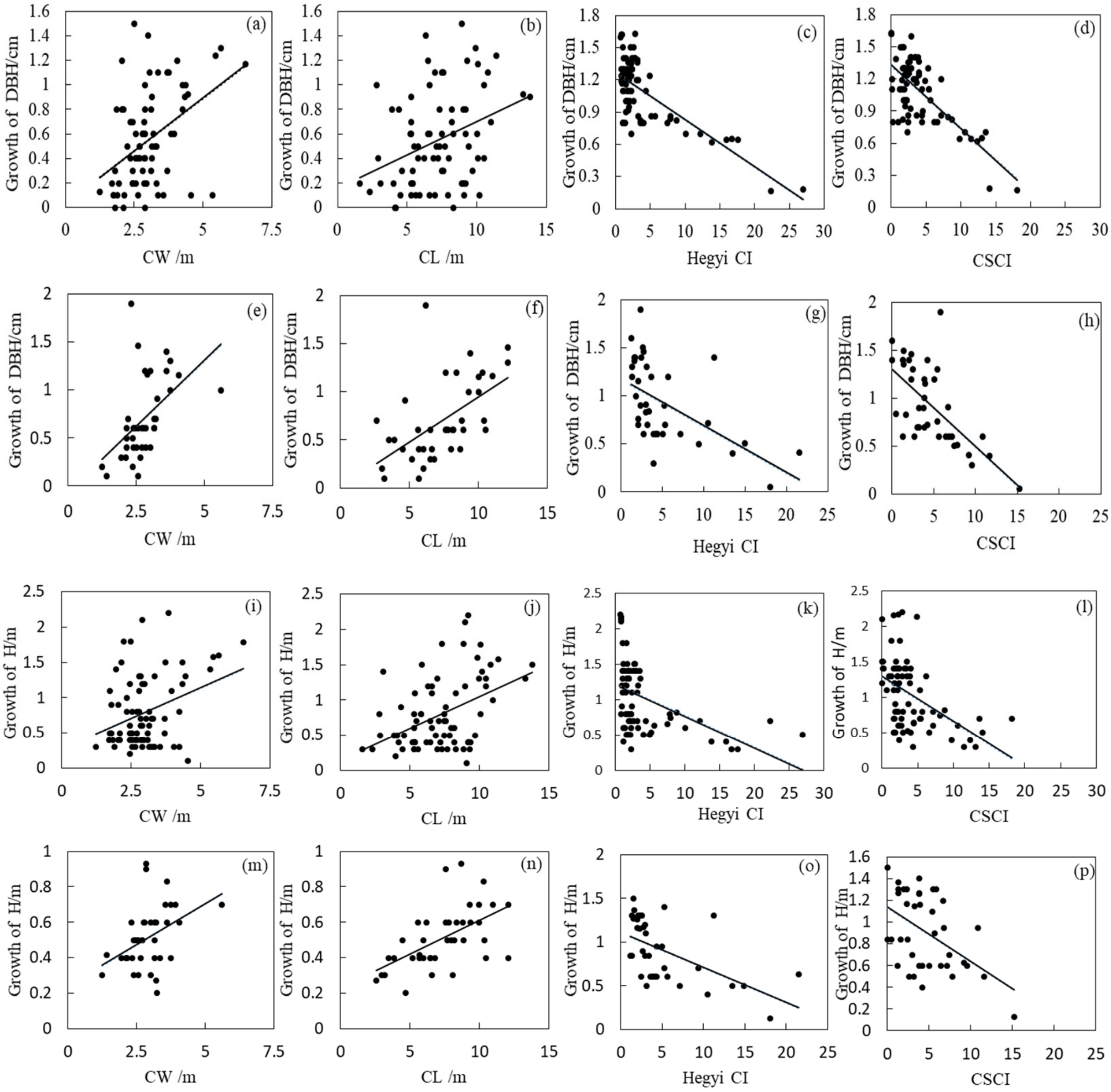

Figure 6. Scatter plots of the annual growth increment in DBH and tree height versus crown width, crown length, Hegyi Competition Index, and Crown Size Competition Index ((**a**–**d**,**i**–**l**) for *Cunninghamia lanceolata*, (**e**–**h**,**m**–**p**) for *Phoebe bournei*).

Table 4. Pearson correlation coefficient of the annual growth increment in DBH and tree height with CW, CL, Hegyi CI, and CSCI.

Tree Species	Annual Growth Increment	CW	CL	Hegyi CI	CSCI
CL	DBH	0.436 **	0.350 **	−0.707 **	−0.728 **
	Height	0.339 **	0.443 **	−0.467 **	−0.475 **
PB	DBH	0.498 **	0.562 **	−0.556 **	0.654 **
	Height	0.427 **	0.565 **	−0.485 **	−0.551 **

** indicates that the correlation is significant at a confidence level (two-sided) of 0.01; *CL*: *Cunninghamia lanceolata*; *PB*: *Phoebe bournei*; Hegyi CI: Hegyi Competition Index; CSCI: Crown Size Competition Index; CW: Crown width; CL: Crown length.

The CSCI and Hegyi CI were computed for each focal tree of *CL* and *PB*. The correlation coefficients between these two competition indices and the annual growth increment in tree stem volume were calculated (Table 5), evaluating the strength of the correlation degree to assess the competition index model. The study's results (Table 5) indicated that both the CSCI and Hegyi CI for *CL* and *PB* exhibited significant correlations with the annual growth increment in tree stem volume at the 0.01 significance level. The absolute values of Kendall's tau-b, Spearman's rho, and Pearson correlation coefficient for CSCI and annual growth increment in tree stem volume were greater than those for the Hegyi CI. This suggests that the CSCI exhibits a stronger correlation with tree annual growth increment in stem volume compared to the Hegyi CI, indicating that the former more appropriately captures the relationship between tree competition and growth.

Table 5. Correlation analysis between the competition index and the annual growth increment in tree stem volume.

Tree Species	Correlation Coefficient	Crown Size Competition Index	Hegyi Competition Index
Cunninghamia lanceolata	Kendall's tau-b	−0.535 **	−0.278 **
	Spearman's rho	−0.700 **	−0.395 **
	Pearson	−0.494 **	−0.416 **
Phoebe bournei	Kendall's tau-b	−0.601 **	−0.374 **
	Spearman's rho	−0.790 **	−0.525 **
	Pearson	−0.493 **	−0.490 **

Note: ** indicates that the correlation is significant at a confidence level (two-sided) of 0.01.

3.3. The Effect of Neighborhood Tree Species Diversity on Tree Competition

We computed the species diversity of the neighborhood (competing tree) for each focal tree, characterizing neighborhood species diversity by the degree of mingling. The scatter plot illustrating the relationship between the Hegyi CI and the degree of mingling (Figure 7a) reveals that when the focal tree is *CL*, there are five values of neighborhood species diversity, primarily distributed between 0, 0.25, 0.5, and 0.75. The number of trees at a mingling degree of 1 is relatively small, indicating fewer instances where the neighborhood species are all different from *CL*. More commonly, the neighbors are either all *CL*, or the number of trees in the neighborhood (one, two, and three trees) consists of *CL*. In cases of moderate and weak mingling (Mingling = 0.5, 0.25), the competitive index of the tree is larger, suggesting that proper mingling facilitates competitive growth in the stand. The scatter plot illustrating the relationship between the CSCI and the degree of mingling (Figure 7b) displays 15 values of neighborhood species diversity (Mingling) obtained by determining the number of stands within the neighborhood by crown size. These values are primarily distributed at 0.25 and 0.5, indicating that 25% and 50% of the neighboring trees have the highest proportion of different species from the focal tree. When *PB* is the focal tree (Figure 7c), trees in moderate (Mingling = 0.5) and intense (Mingling = 0.75) mixes exhibit a larger CSCI. Additionally, trees in moderate (Mingling = 0.5) and very intense

(Mingling = 1) mixes show a larger CSCI (Figure 7d). From the analysis, it is evident that the two tree species exhibit different sensitivities to neighborhood diversity and composition. Higher neighborhood species diversity has a greater effect on the competitive intensity of the focal tree. The neighborhood effect is more pronounced for broadleaved species (*PB*) than for coniferous species (*CL*).

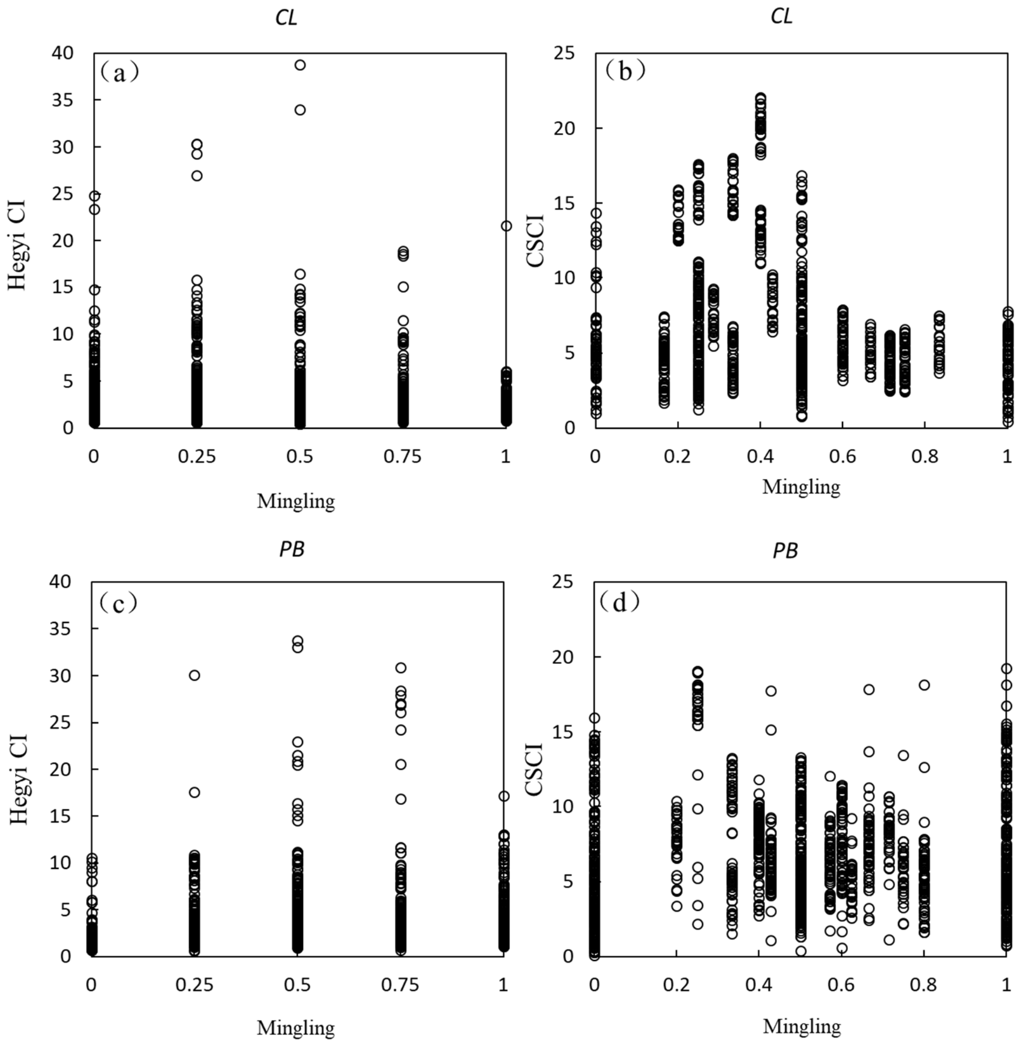

Figure 7. Scatter plot of Mingling in relation to Hegyi Competition Index and Crown Size Competition Index (*CL* for *Cunninghamia lanceolata*, *PB* for *Phoebe bournei*). (**a**) is the scatter plot of Hegyi Competition Index versus Mingling for *Cunninghamia lanceolate.* (**b**) is the scatter plot of Crown Size Competition Index versus Mingling for *Cunninghamia lanceolate.* (**c**) is the scatter plot of Hegyi Competition Index versus Mingling for *Phoebe bournei.* (**d**) is the scatter plot of Crown Size Competition Index versus Mingling for *Phoebe bournei.*

4. Discussion

4.1. Interactions between the Focal Tree and Their Neighboring Trees

We discovered evidence supporting complementary effects on individual tree growth in *CL* and *PB*, facilitated to a moderate extent by increased diversity of neighboring species. These effects arise due to variations in the strength of intraspecific and interspecific interactions [43]. In line with prior research, our findings indicate that competition intensity is higher in *PB* compared to *CL*. Notably, *CL*, with its larger crown, demonstrates relative insensitivity to competition. Additionally, *CL* tends to grow taller than *PB*, allowing it to benefit from asymmetric competition for light. Furthermore, scholars have observed that the competition index of *CL*, when serving as the focal tree in CLPB mixed forests, is lower than that in pure *CL* forests. The intensity of intraspecific competition in *CL* decreases with an increase in the proportion of *PB* [50]. The ecological relationships between trees are complex, both among individual trees and between focal trees and their neighbors [51]. Luu T C [52] explored the impact of neighborhood uniformity on the growth of individual trees in Eucalyptus monocultures and investigated competition between pioneer and non-pioneer species in mixed restoration plantations of native species. They developed a range of alternative neighborhood growth models, revealing that the uniformity of tree sizes in the neighborhood significantly influenced the growth of individual clonal Eucalyptus trees. In the context of competition from pioneer to non-pioneer trees, neighboring trees exerted strong effects on the growth of individual non-pioneer trees. The intensity of competition varied based on the species of the focal tree and the degrees of silviculture interventions [53,54]. Through statistical analysis of the number of neighboring trees around focal tree within the stand, we found that the majority of focal trees have two to five neighboring trees. Having too few or too many neighboring trees around a focal tree is detrimental to the competition and growth of the tree.

There may be intense competition for resources between the focal tree and neighboring trees, or there may be a promotional relationship [55]. Boyden [56] investigated changes in the nature and strength of interactions between *Eucalyptus* trees and the nitrogen-fixing plant *Falcataria mollucana* along a gradient of soil nitrogen and phosphorus supply in Hawaii, USA. Using a proximity index to describe competitive and facilitative interactions between trees and a spatially explicit model for the growth and survival of individual trees, the study found that the dynamics between neighboring trees heavily depended on soil nutrient availability. While larger trees generally grew faster than smaller ones, the interaction between nutrient supply and the intensity of competition and facilitation moderated this pattern. The crucial role of soil nutrient supply in regulating the strength and nature of tree interactions implies that studies on competition and facilitation should consider a broad range of soil conditions to ensure generalizability. Notably, there is a scarcity of studies explicitly investigating the effects of neighborhood diversity on tree growth. Pretzsch [55] demonstrated the positive effects of local neighborhood mingling on biomass production. Examining the effects of mingling in beech–Norwegian spruce forests from the monoculture level up to the plot level, the study elucidated different mechanisms behind each species' response to mingling. Findings revealed that in mixtures of the two species, overproduction at the plot level was attributed to a facilitating effect of beech on Norway spruce and a reduction in intraspecific competition between beech trees.

4.2. Neighborhood Species Diversity and Tree Competition

Our findings underscore the significant influence of neighborhood species diversity on tree competition dynamics within mixed forests. We observed that higher neighborhood species diversity corresponded to increased competitive intensity, particularly affecting the growth of broadleaved species like *PB* [57]. This suggests that species composition plays a crucial role in shaping competitive interactions among trees [58]. Furthermore, our results support the hypothesis that broadleaved species exert a greater influence on focal tree competition compared to coniferous species. Understanding the effects of neighborhood species diversity on tree competition is vital for informing forest management strategies aimed at promoting biodiversity and ecosystem resilience [59]. By considering species composition and diversity in forest management decisions, practitioners can better anticipate and mitigate the impacts of competition, ultimately fostering healthier and more sustainable forest ecosystems. Research by Garcia et al. in European mixed forests demonstrated that broadleaved species exerted a greater influence on focal tree competition compared to coniferous species, supporting our hypothesis (3). Their study underscored the importance of considering species composition in forest management decisions to mitigate the impacts of competition and promote ecosystem resilience [60].

Scholars have noted that it is the local assemblage of species (small-scale mixing) that affects tree growth, rather than the number or diversity of species in the stand as a whole, and that diversity at the neighborhood level improves productivity at the stand level [26]. In our study, *CL* provides shade for *PB*, significantly enhancing its productivity [61]. Simultaneously, the presence of *PB* creates favorable conditions for *CL* to compete for growth, aiming to secure more sunlight. These stands hold promise for establishing and maintaining mixed-species, multi-group, stratified stands. These findings align with "free-range" and "near-natural" forest management, emphasizing a heterogeneous stand structure and providing a mosaic of different tree species.

4.3. Competition Indices

Competition occurs among trees due to the limitation of resources such as sunlight, water, and nutrients. This competition has significant effects on the growth and development of trees. Competition indices are tools used to quantify and assess the intensity of tree competition, typically considering the interactions among trees as well as their interactions with the surrounding environment. Additionally, the size of a tree's crown is closely related to its ability to acquire environmental resources. Therefore, incorporating crown characteristics into competition indices may be more suitable for representing the competitive pressure experienced by trees.

In this study, we introduced a novel competition index, termed the Crown Size Competition Index, incorporating four factors—tree height, tree position, under-branch height, and crown width. These factors were chosen to reflect both the inherent biological characteristics of trees and their resource acquisition capabilities. Calculations of the CSCI for each focal tree revealed a competitive trend consistent with the Hegyi CI. Importantly, the results indicated a stronger correlation between the CSCI and tree growth compared to the Hegyi CI. Consequently, we infer that integrating the crown factor into the competition index model enhances its accuracy in reflecting the competitive dynamics among trees within stands. Understanding forest competition and the interrelationships between competition indices and tree growth is therefore essential for effective management and conservation of forest ecosystems. Attempts to use a single competition index model to reflect the competitive relationships between trees in complex stands are incomplete, so more in-depth and extensive research on competition index models is needed.

5. Conclusions

With the increasing focus on near-natural forest management, mixed forests, especially those combining coniferous and broadleaved trees, are receiving more attention. *CLPB* mixed forests, which blend fast-growing *CL* trees with the rare *PB* species, emerge as a vital strategy for balanced development. Our study reveals accelerated growth of *CL* and *PB* trees in diverse neighborhood conditions, influencing crown sizes and competitive dynamics. *CL* generally has a longer crown, while *PB* has a wider one. We found a significant correlation between the annual growth increment in stem volume and the competition index, particularly with the CSCI. Increased competition from neighboring trees reduces volume growth, especially for *PB*. Neighboring species diversity affects competition intensity, with *PB* exerting a stronger impact than *CL*. These insights highlight the competitive advantages of *CL* and rare *PB* in mixed forests, guiding management practices. Notably, while distance-independent competition indexes reflect individual dominance, the CSCI offers a more objective assessment of tree competition, reflecting actual competitive dynamics among trees.

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