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Stand Stability of Pure and Mixed-*Eucalyptus* Forests of Different Tree Species in a Typhoon-Prone Area

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Abstract: *Background and Objectives*: The stable stand structure of mixed plantations is the basis of giving full play to forest ecological function and benefit. However, the monocultural *Eucalyptus* plantations with large-scale and successive planting that caused ecological problems such as reduced species diversity and loss of soil nutrients have presented to be unstable and vulnerable, especially in typhoon-prone areas. The objective of this study was to evaluate the nonspatial structure difference and the stand stability of pure and mixed-*Eucalyptus* forests, to find out the best mixed pattern of *Eucalyptus* forests with the most stability in typhoon-prone areas. *Materials and Methods*: In this study, we randomly investigated eight plots of 30 m × 30 m in pure and mixed-*Eucalyptus* (*Eucalyptus urophylla* S. T. Blake × *E. grandis* W. Hill) plantations of different tree species (*Neolamarckia cadamba* (Roxb.) Bosser, *Acacia mangium* Willd., and *Pinus elliottii* var. *Elliottii* Engelm. × *P. caribaea* Morelet) on growth status, characterized and compared the distribution of nonspatial structure of the monoculture and mixtures, and evaluated the stand quality and stability from eight indexes of the nonspatial structure, including preservation rate, stand density, height, diameter, stem form, degree of stem inclination, tree-species composition, and age structure. *Results*: *Eucalyptus* surviving in the mixed plantation of *Eucalyptus* and *A. mangium* (EA) and in the mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP) were 5.0% and 7.6% greater than those in pure *Eucalyptus* plantation (EE), respectively, while only the stand preservation rate of EA was greater (+2.9%) than that of the pure *Eucalyptus* plantation. The proportions of all mixtures in the height class greater than 7 m were fewer than that of EE. The proportions of EA and mixed plantation of *Eucalyptus* and *N. cadamba* (EN) in the diameter class greater than 7 m were 10.6% and 7.8%, respectively, more than that of EE. EN had the highest ratio of branching visibly (41.0%), EA had the highest ratio of inclined stems (8.1%), and EP had the most straight and complete stem form (68.7%). The stand stability of the mixed plantation of *Eucalyptus* and *A. mangium* presented to be optimal, as its subordinate function value (0.76) and state value (ω = 0.61) of real stand were the largest. *Conclusions*: *A. mangium* is a superior tree species to mix with *Eucalyptus* for a more stable stand structure in the early growth stage to approach an evident and immense stability and resistance, which is of great significance for the forest restoration of *Eucalyptus* in response to extreme climate and forest management.

Keywords: mixed forest; preservation rate; stability; stem form; nonspatial structure

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1. Introduction

As a fast-growing tree species, *Eucalyptus* has been introducing and promoting genetic improvement in many regions to produce large amounts of wood for economic development [1]. However, large-area planting and continuous-planting rotation of commercial *Eucalyptus* plantations have caused various problems, such as reduced species diversity and loss of soil nutrients, which threaten ecological and timber security regionally and worldwide [1–5]. Constructing mixed forests can form a stratified stand structure, which helps to make full use of the forest land space and environmental resources, increase light energy utilization, regulate the climatic environment within and outside the forest, improve forest land environment, improve forest productivity, increase species diversity, enhance the forests' ability to resist the disaster, exert forest ecological protection benefits, and promote the ecological balance [6–8]. Therefore, it is necessary to choose suitable and superior tree species to build a mixed-*Eucalyptus* plantation characterized by a fast-growing, high-yield, high-resistance, richly diverse, and stable ecosystem. Nevertheless, the growth of mixed plantations is mainly restricted by the choice of the site and tree species, the collocation of row spacing, and the mixing proportion and pattern. In view of the complexity of these factors, it is still difficult to mix different tree species with *Eucalyptus* in line with expectations and to ensure the ecological and economic benefits, and to realize sustainable development of *Eucalyptus* plantations.

In consulting and reviewing the literature, we found that most studies on mixed-*Eucalyptus* plantations have focused on light or water use [8,9], productivity [4,10,11], carbon allocation [11–15], nutrient cycle [6,16–18], microbial communities [19,20], or succession dynamics [21,22], and less research has been done on the structural features of mixed-*Eucalyptus* plantations. Forest structure determines the service function of forest ecosystems by influencing the forest environment and biological factors [23]. A reasonable stand structure is not only the basis of giving full play to forest function and benefit [24], but also the main driving force of forest ecosystem succession. The study of stand structure is the theoretical basis of the forest management and analysis, and the comprehensive reflection of stand-development processes such as tree-species competition, natural succession, and disturbance activities [25]. The stand structure includes spatial structure and nonspatial structure [26–29]. Spatial structure, generally using mingling, neighborhood comparison, uniform angle index, open degree, competition index, and forest layer index for evaluation, mainly refers to the point pattern of individuals and the spatial distribution of their attributes. Nonspatial structure, which is evaluated by factors reflecting stand characteristics, including the tree-species composition, the stand density, the tree height distribution, the diameter distribution, the canopy structure, the tree-species diversity, the tree vigor, the tree stability, etc., generally describes the average state of stand structural characteristics, which is independent of the spatial properties of single trees. The distribution structure of these characteristic factors can reflect the overall stability and resistance of the forest and the quality of the stand, to some extent [30–33]. Peng analyzed the age structure of the forest community and the species diversity of each age level, and then concluded that the age structure of the forest community can represent the stability and succession dynamics of the community [34]. The research results of O'Connor et al. showed that the population structure of tree species had a significant influence on stability, which could be used as a conclusion for future stability [35]. Through the study of the structure of stands, we can understand their distribution rules and the interaction relationship between tree species [24] to provide theoretical guidance for forest management. The spatial structure of pure *Eucalyptus* forests is particularly monotonous. We hypothesized that the structure of *Eucalyptus* plantations mixed with other tree species would improve and change greatly, and the stand stability and stress resistance on resisting external adverse disturbance would be enhanced tremendously, indicating the correct selection of mixed species and the success of mixed pattern. In windy areas, a forest with a successful mixed pattern can slow down wind speed and reduce the economic loss caused by wind damage, which is also the full embodiment of ecological function [36–38]. Therefore, it is of great significance to study the stand structure of *Eucalyptus* plantations mixed with different tree species, especially the *Eucalyptus* plantations in windy areas.

Taking the preservation rate, stand density, height, diameter, stem form, degree of stem inclination, tree-species composition, and age structure as evaluation indexes of the nonspatial structure, this paper aims to analyze the structural difference of *Eucalyptus* (*Eucalyptus urophylla* S. T. Blake × *E. grandis* W. Hill) plantations of the monoculture and mixtures that are respectively combined with three different tree species (*Neolamarckia cadamba* (Roxb.) Bosser, *Acacia mangium* Willd., and *Pinus elliottii* var. *Elliottii* Engelm. × *P. caribaea* Morelet). Embarking from the actual growth status of each plantation, this study explored the stand stability and resistance of the monoculture and mixtures of *Eucalyptus* forests and discovered the best composition and pattern of *Eucalyptus* mixed with tree species in typhoon-prone areas.

2. Materials and Methods

2.1. Site Characteristics

The experimental field was located on the Leizhou Peninsula (20°57′ N, 109°48′ E), Zhanjiang City, Guangdong Province (Figure 1), with an elevation of 35 m and a gentle terrain with a nearly 0° slope. The region is dominated by a tropical maritime monsoon climate with a mean annual temperature of 23.5 °C, a mean annual precipitation of 1690.7 mm, and a relative humidity of 81.0%, presenting an dry and wet seasons (May–September: rainy season, with south wind blowing mainly; and October–April: dry season, with north wind blowing mainly). Frequent tropical storms or typhoons reach land on the Leizhou Peninsula 1–3 times every year; these are the primary natural calamities in the Leizhou Peninsula. When a typhoon lands, the rainfall amount increases in some areas, the temporary water accumulations happen in low-lying areas, some trees are blown off, and the tree wounds are easily infected with bacteria. Along with strong wind, heavy rainfall, and storm surge, typhoon landings cause serious economic losses and social impact in Zhanjiang City every year, including casualties, crop damage, house collapse, building destruction, and production stagnation [39,40].

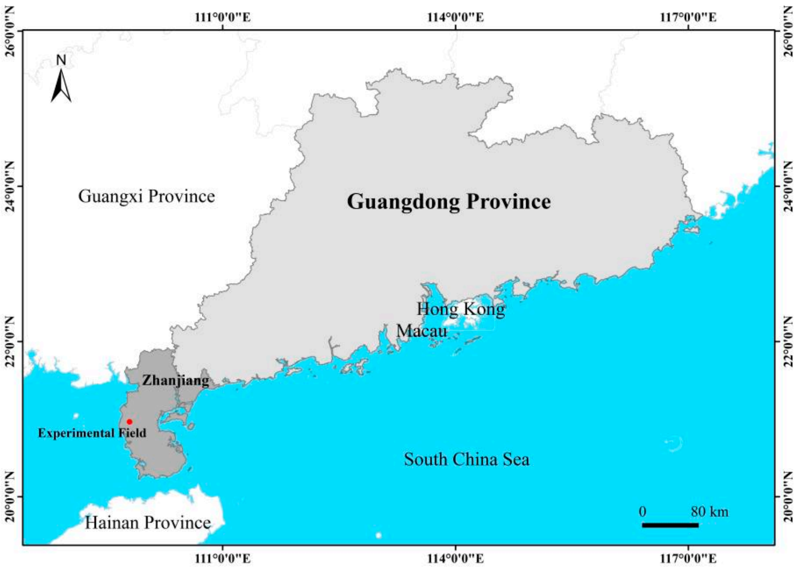


Figure 1. Location of the experimental field in Zhanjiang City, Guangdong Province, China.

2.2. Characteristics of the Experimental Plantations

These experimental plantations were constructed in February 2014 and included one pure plantation of *Eucalyptus urophylla* S. T. Blake × *E. grandis* W. Hill "DH32-29" (EE) as the control, and three mixed-*Eucalyptus* (DH32-29) plantations mixed with three kinds of tree species: (1) a mixed plantation of *Eucalyptus* and *Neolamarckia cadamba* (Roxb.) Bosser (EN) that was mixed by strip for four rows of *Eucalyptus* and four rows of *N. cadamba*; (2) a mixed plantation of *Eucalyptus* and *Acacia mangium* Willd. (EA) that was mixed by strip for four rows of *Eucalyptus* and four rows of *A. mangium*; and (3) a mixed plantation of *Eucalyptus* and *Pinus elliottii* var. *Elliottii* Engelm. × *P. caribaea* Morelet (EP) that was mixed by row for one row of *Eucalyptus* and one row of *P. elliottii* × *P. caribaea*. Since the biological characteristics of the different tree species are intrinsically different, *Eucalyptus* DH32-29 and *P. elliottii* × *P. caribaea* were planted with a spacing of 1.3 m × 3.0 m, *N. cadamba* was planted with a spacing of 3.9 m × 3.0 m, and *A. mangium* was planted with a spacing of 2.6 m × 3.0 m. They are all fast-growing excellent tree species with strong adaptabilities to grow in the Leizhou Peninsula. However, they were damaged annually by severe wind damages after planting (Table 1). Due to the catastrophic damage of the typhoon "Mujigae" (Super Typhoon, wind force $\geq$ 52 m/s, Beaufort scale $\geq$ 16) in October 2015, all *Eucalyptus* trees were blown down with stems broken; hence, all *Eucalyptus* were cut off from the basal stem to facilitate the germination of new branches and renew the whole stands. Recovery measures that erected leaning or fallen trees were taken for mixed species to restore stands. In June 2016, one strong branch was preserved and the others were removed. Other tending measures were consistent across the four stands.

Table 1. Appearance situation of tropical cyclones on the Leizhou Peninsula from 2014 to 2017.

Landing Date	Name	Number Code	Maximum Wind Speed at Landfall (m/s)	Beaufort Scale	Intensity Rank
18 July 2014	Rammasun	1409	72	17	Super Typhoon (SuperTY)
16 September 2014	Kalmaegi	1415	42	13	Severe Typhoon (STY)
4 October 2015	Mujigae	1522	52	16	Super Typhoon (SuperTY)
18 August 2016	Dianmu	1608	28	8	Tropical storm (TS)

2.3. Data Measurements

By the end of April 2017, two plots of 30 m $\times$ 30 m were set randomly in each stand type (including three mixed stands and one pure stand), adopting the random sampling method to measure the height, diameter, straight-fullness, and brunching status of stem form; the stem inclination of each tree; as well as to record the number of preserved and missing trees. The height (H, unit: m) was measured with a laser altimeter (Nikon Rangefinder Rieho 1000 AS) (precision: 0.1 m). The diameter at breast height (DBH, unit: cm) of each individual tree was measured with a tape (precision: 0.1 cm). Both the stem form and the degree of inclination of each tree were evaluated by the classification methods as described in Table 2 and Figures 2 and 3 for statistics. The classification criteria on growing status of tree stem were set mainly based on the studies [41–43] of Zhao et al., Zhu et al., and Pelletier et al.

Table 2. Classification criteria on growing status of tree stems [41–43].

Stem Form		Degree of Stem Inclination	
Classification	**Description**	**Classification**	**Description**
I (Assigning a score of 6)	The tree has one single principal stem that is complete and straight (well-formed).	I (Assigning a score of 6)	The tree stem grows vertically without leaning to any side.
II (Assigning a score of 5)	The tree has one single principal stem that is complete and curved slightly.	II (Assigning a score of 5)	The tree stem has an inclination of 0° to 30° from the vertical axis.
III (Assigning a score of 4)	The tree has more than two principal stems that are branched below a third of its height.	III (Assigning a score of 4)	The tree stem has an inclination of 30° to 60° from the vertical axis.
IV (Assigning a score of 3)	The tree has more than two principal stems that are branched higher than one-third and lower than two-thirds of its height.	IV (Assigning a score of 3)	The tree stem has an inclination of 60° to 90° from the vertical axis.
V (Assigning a score of 2)	The tree has more than two principal stems that are branched higher than two-thirds of its height.	V (Assigning a score of 2)	The treetop was broken off.
VI (Assigning a score of 1)	The tree has one single stem that is bent badly.	VI (Assigning a score of 1)	The tree stem was broken off.

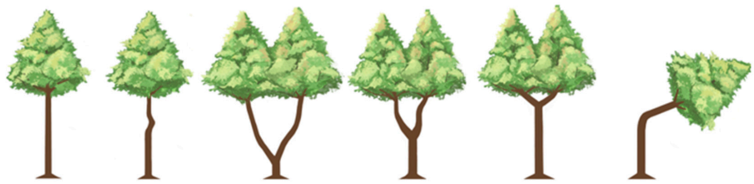


Figure 2. Classification criteria on stem form and silhouettes of tree stems.

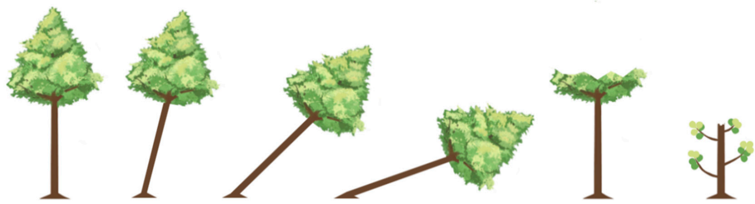


Figure 3. Classification criteria on degree of stem inclination and silhouettes of tree stems.

2.4. Data Processing and Statistical Analysis

Eight indicators of nonspatial structure were assigned: preservation rate, stand density, height, diameter, stem form, degree of stem inclination, tree-species composition, and age structure. The preservation rate means the percentage of tree survival after a period of afforestation, which indicates the degree to which trees are kept safe from damage of external disturbance. The calculation formula is as follows:

$$P = \frac{n_0}{N_0} \times 100\%, \tag{1}$$

where P is the preservation rate of each stand, n_0 is the number of retained plants, and N_0 is the number of planted plants.

The tree height distribution was calculated by using the tree height class integration method: every 2 m was integrated as one tree height class, and the median value of the group represented the tree height class and was involved in the calculation. The diameter distribution was calculated by using the diameter class integration method: every 2 cm was integrated as one diameter class, and the median value of the group represented the diameter class and was involved in the calculation. The stem form and inclination status of the stem were analyzed through their classification.

In the experimental field, two tree species and two ages exist in each mixed forest, one tree species and one age exist in the pure forest; hence, both the tree-species composition structure and age structure of the mixed forest were assigned a value of 2.00 when evaluating the stand stability of each forest, while that of the pure forest was assigned a value of 1.00. Other evaluation indexes were assigned as their average values. The values of the stability indexes were standardized first by adopting the method of subordinate function value of fuzzy mathematics [44–46] and forward to make it dimensionless between 0 and 1.00. The formula is as follows:

$$U_{ij} = \frac{(x_{ij} - x_{i\min})}{(x_{i\max} - x_{i\min})}, \tag{2}$$

where U_{ij} is the subordinate function value of i index of j stand, $U_{ij} \in (0, 1.00)$; x_{ij} is the measured value of i index of j stand; $x_{i\min}$ is the minimum value of i index of j stand; and $x_{i\max}$ is the maximum value of i index of j stand.

The stability of the four *Eucalyptus* forests was assessed by the unit circle analysis method of π value rule of optimal stand state [47,48]. According to the method of π value rule of optimal stand state [48], when the values of all stand-state indicators are equal to one, the closed chart area formed is the largest and is equal to the unit circle area π, which can be regarded as the expected value of the optimal stand state. Therefore, the best stand state value (expected value) always equals the unit circle area π, namely the rule of π value of the best stand state. Hence, the stand state depends on the size of the closed chart area composed of real stand-state indicators, and the ratio of the real stand-state value (the size of closed chart area) to the optimal stand-state value (expected value) is the most appropriate measurement of the real stand quality [48]. The methods are as follows: Draw a circle with a radius of 1.00 and divide the circle of 360° into eight sector areas, which represent eight nonspatial structure indexes of the stand, respectively. Starting from the center of the circle of the eight sector areas, draw corresponding index lines in the form of radiation and mark the index names. Sort the corresponding index value of each stand from large to small and mark them on the radiation with points. Connect adjacent points in turn to form a closed curve, which represents the stability state of the real stand.

When all indicators are equal to one, the maximum circular area of π can be regarded as the optimal stand state. The ratio of the state value of the real stand to the optimal stand is used to judge the stable degree of the state value of the real stand, and the formula is:

$$\omega = \frac{s_1 + s_2}{\pi} = \frac{\frac{\pi(m-1)}{n} + \sum_{i=1}^{n-m+1} s_{2i}}{\pi},\ m \geq 1 \tag{3}$$

$$\omega = \frac{s_2}{\pi} = \frac{\sum_{i=1}^{n} s_{2i}}{\pi},\ m = 0 \tag{4}$$

$$s_{2i} = \frac{\sin\theta}{2} L_1 L_2 \tag{5}$$

where ω is the stable degree of the state value of the real stand; s_1 is sum of all sector areas in a closed figure; s_2 is sum of the areas of all triangles in a closed figure; n is the number of indicators ($n \geq 2$); m is the number of indicators equal to 1; L_1 and L_2 are values of two adjacent indicators in the triangle part, respectively; and θ is the angle formed by two adjacent indicators.

Therein, $\omega \in (0, 1.00)$. It indicates an excellent status when $\omega \geq 0.70$. A good status is indicated when $\omega \in (0.55, 0.70)$. A general status is indicated by $\omega \in (0.40, 0.55)$. It indicates a poor status when $\omega \in (0.25, 0.40)$. A terrible status is indicated when $\omega \leq 0.25$.

Microsoft Excel 2007 (Version 2007, Redmond, Washington D.C., USA) was used for data processing, R software (Version 3.5.1, Auckland, Auckland metropolitan area, New Zealand) was used for data analysis, and Python (Version 3.8, Amsterdam, Noord-Holland, the Kingdom of the Netherlands) was used for drawing the figure of stand-state unit circles.

3. Results

3.1. Preservation of Eucalyptus Pure and Mixed Plantation

The preservation rates varied in tree species and stands, as shown in Table 3. Regarding the tree species in each experiment plantation, *Eucalyptus* surviving in EA and EP were 5.0% and 7.6% greater than those in the pure *Eucalyptus* forest (EE), respectively, while *Eucalyptus* surviving in the EN mixture was 18.8% fewer than those in EE. Therefore, both *A. mangium* and *P. elliottii* × *P. caribaea* had positive effects on the preservation of *Eucalyptus*. Among the mixed species, *N. cadamba* survived the most, at 88.9%, *A. mangium* survived at 59.3%, and *P. elliottii* × *P. caribaea* survived the least, at 50.2% (Table 3). As for the whole stand, the preservation rates of pure and mixed-*Eucalyptus* plantations demonstrated in Table 3 were all at a rather lower level (less than 70%) after experiencing severe wind damage four times, and only the preservation rate of EA was 2.9% greater than that of EE.

Table 3. Preservation rate of pure and mixed-*Eucalyptus* plantations (unit: %).

Stand Type	*Eucalyptus*	Mixed Species	Stand
EN	41.6	88.9	49.9
EA	65.4	59.3	63.3
EP	68.0	50.2	59.7
EE	60.4	—	60.4

3.2. Tree Height Distribution

The distribution pattern of tree height structures of 18-month-old *Eucalyptus* was demonstrated to be similar in the pure and mixed-*Eucalyptus* forests (Figure 4). The tree height class of 7 m of *Eucalyptus* received the largest percentage in four stands, followed by that of 9 m. As for 38-month-old mixed tree species, only the tree height distributions of *N. cadamba* and *A. mangium* were similar, since the number of trees with a height class of 7 m was the largest, followed by that of 5 m. The number of trees with a height class of 3 m was the largest in EP. All the mixed-*Eucalyptus* forests were demonstrated to be unevenly aged, multistoried structures (Figure 4).

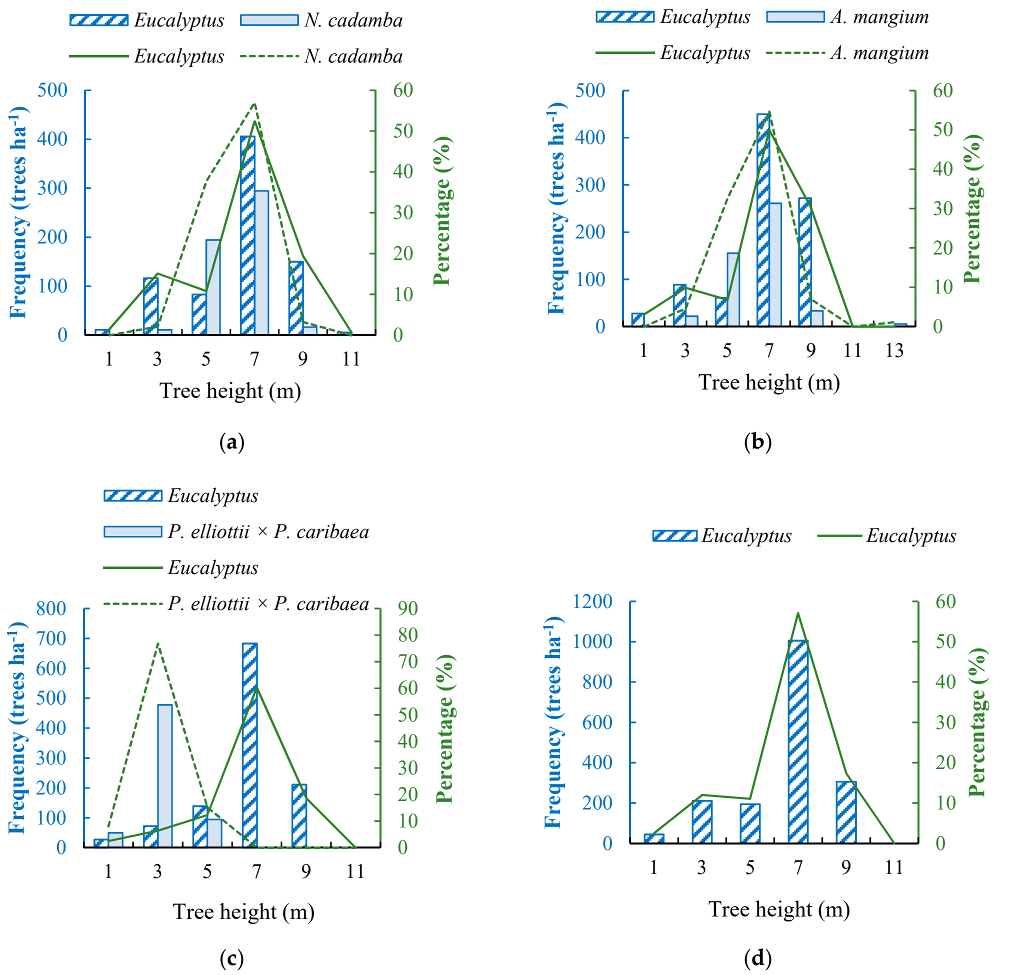


Figure 4. Tree height distribution of *E. urophylla* × *E. grandis* at the age of 18 months and of mixed tree species at the age of 38 months in the monoculture and mixtures. Height of the histograms shows the distribution frequency of tree height of each tree species per hectare. The line shows the distribution percentage of tree height of each tree species per hectare. (**a**) Mixed plantation of *Eucalyptus* and *N. cadamba* (EN); (**b**) mixed plantation of *Eucalyptus* and *A. mangium* (EA); (**c**) mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP); (**d**) pure forest of *E. urophylla* × *E. grandis* (EE).

Regarding the four forests of pure *Eucalyptus* and mixtures, the tree heights of EA were mainly distributed from 6.00 to 10.00 m (51.6% for the height class of 7 m and 22.2% for the height class of 9 m), which was identical with that of EE (Table 4). However, the tree heights of EN and EP were lower than that of EE in that tree heights of EN were mainly distributed from 4.00 to 8.00 m (21.6% for the height class of 5 m and 54.3% for the height class of 7 m), and tree heights of EP were mainly distributed from 2.00 to 4.00 m (31.3%) and 6.00 to 8.00 m (39.0%). In addition, even though the proportion of height class that was greater than 7 m of *Eucalyptus* was EA > EP > EE > EN from high to low in sequence, the proportion of height class that was greater than 7 m in EA was similar to EE (0.3% less), and that in EN and EP were 6.9% and 23.5%, respectively, less than that in EE (Table 4).

Table 4. Tree height distribution of pure *Eucalyptus* forest and mixed-*Eucalyptus* forest.

Stand Type	Height Class (Unit: m)													
	1		3		5		7		9		11		13	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
EN	11	0.9	128	9.9	278	21.6	700	54.3	167	12.9	5	0.4	0	0
EA	28	2.0	111	8.1	217	15.7	711	51.6	306	22.2	0	0	5	0.4
EP	78	4.4	550	31.3	233	13.3	684	39.0	211	12.0	0	0	0	0
EE	44	2.5	211	12.0	194	11.0	1006	57.1	306	17.4	0	0	0	0

Note: N is the number of retained plants per hectare corresponding to the height class.

3.3. Diameter Distribution

The diameter distribution of *Eucalyptus* in the different mixtures resembled that of EE: the diameter class of 7 cm accounted for the largest proportion, followed by the 9 cm diameter class, in spite of some subtle differences being demonstrated among the four stands (Figure 5). With regard to mixed tree species, both the diameter distribution of *N. cadamba* and *A. mangium* were exhibited to be two-peak structures and ranged from 4.00 to 12.00 cm mostly, while most diameters of *P. elliottii* × *P. caribaea* ranged from 2.00 to 8.00 cm. The proportion of diameter class greater than 7 cm of *Eucalyptus* from high to low was EP > EA > EN > EE, and that of mixed species from high to low was *A. mangium*, *N. cadamba*, and *P. elliottii* × *P. caribaea*.

It was demonstrated (Table 5) that the distribution of stand diameters of EN and EA were identical to EE for diameters that were mainly distributed in the 7 cm diameter class (ranged from 6.00 to 8.00 cm), followed by the 9 cm diameter class (ranged from 8.00 to 10.00 cm). The diameters of the mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea* were mainly distributed in a diameter class of 7 cm (33.6% ranged from 6.00 to 8.00 cm), followed by a 5 cm diameter class (25.6% ranged from 4.00 to 6.00 cm). Generally, the proportion of diameter class that was greater than 7 cm of stands was EA > EN > EE > EP from high to low (Table 5).

Table 5. Diameter class distribution of pure *Eucalyptus* forest and mixed-*Eucalyptus* forest.

Stand Type	Diameter Class (Unit: cm)															
	1		3		5		7		9		11		13		15	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
EN	28	2.2	161	12.5	195	15.1	422	32.7	300	23.3	133	10.3	39	3.0	11	0.9
EA	28	2.0	122	8.9	222	16.1	456	33.1	361	26.2	139	10.1	50	3.6	0	0
EP	44	2.5	306	17.4	450	25.6	589	33.6	339	19.3	28	1.6	0	0	0	0
EE	55	3.1	267	15.2	339	19.3	728	41.3	372	21.1	0	0	0	0	0	0

Note: N is the number of retained plants per hectare corresponding to the diameter class.

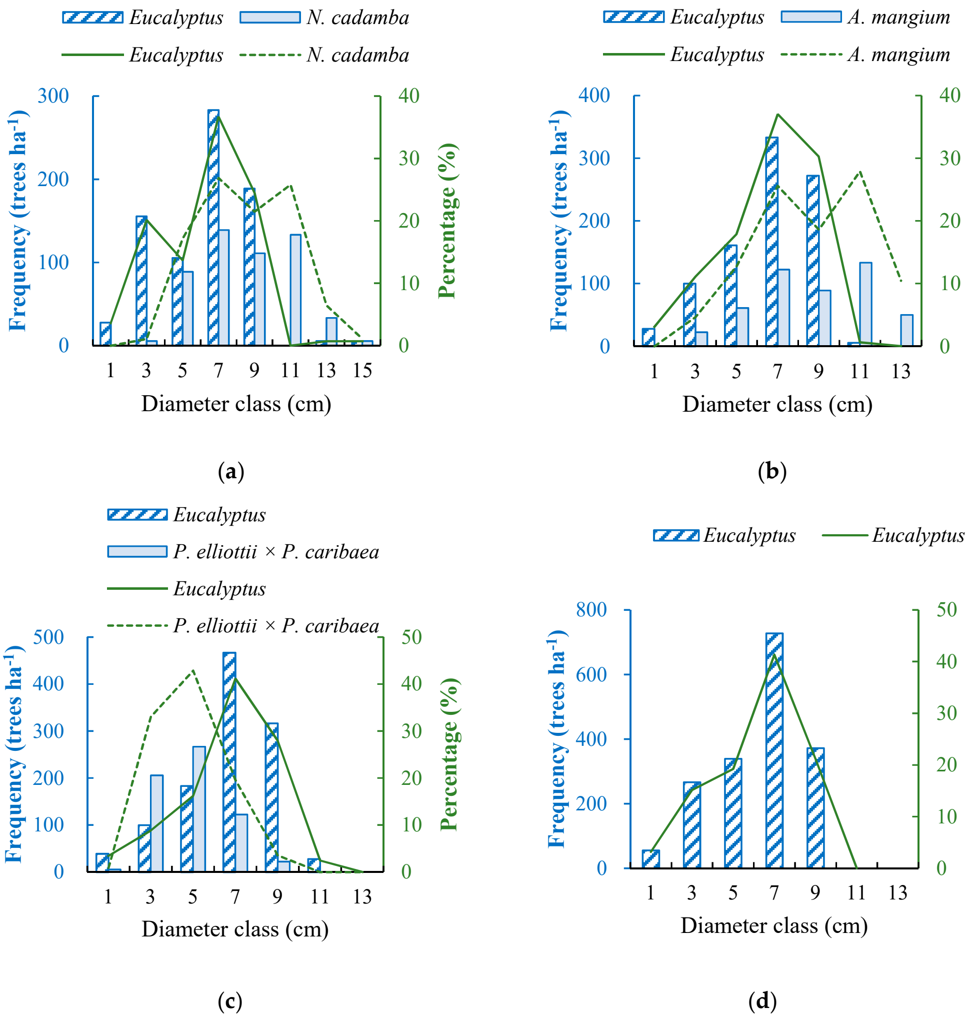


Figure 5. Diameter distribution of *E. urophylla* × *E. grandis* at the age of 18 months and of mixed tree species at the age of 38 months in the monoculture and mixtures. Height of the histograms shows the distribution frequency of diameter of each tree species per hectare. The line shows the distribution percentage of diameter of each tree species per hectare. (**a**) Mixed plantation of *Eucalyptus* and *N. cadamba* (EN); (**b**) mixed plantation of *Eucalyptus* and *A. mangium* (EA); (**c**) mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP); (**d**) pure forest of *E. urophylla* × *E. grandis* (EE).

3.4. Structure of the Tree Stem Form

Apparent differences on the degree of straight-fullness and brunching are demonstrated in Figure 6. In different mixed patterns, only the proportion of straight-fullness of *Eucalyptus* stems in EA was larger than that in EE (1.9% larger in Grade I), and the proportion of branches was lower than that in EE (0.7% lower in Grade III, 3.8% lower in Grade IV, and 0.3% lower in Grade V). The proportion of Grade I *Eucalyptus* stems in EN was 26.2% lower than that in pure forests, and the proportion of Grade III, Grade IV, and Grade V *Eucalyptus* stems was 3.9%, 1.7%, and 6.2% greater, respectively, than that in EE. The stem straight-fullness proportion of *Eucalyptus* in EP was slightly lower than that of EE, and the branches were slightly more than that of EE.

Compared to other mixed species, the degree of straight-fullness and brunching of tree stems of *N. cadamba* in Grade I and Grade II accounted for the smallest proportions of 19.4% and 16.1%, respectively; and in Grade IV and Grade V, accounted for the largest proportions of 29.0% and 31.2%, respectively, indicating that branches of most *N. cadamba* sprouted from a position greater than a third of the height of the tree. Most of *A. mangium* mainly had a single slightly curved stem (46.5% for Grade II), and the proportion of branches of *A. mangium* was substantially greater than that of *Eucalyptus*, but lower than that of

N. cadamba. The majority of *P. elliottii* × *P. caribaea* grew straight and full for Grade I, accounting for 81.3%.

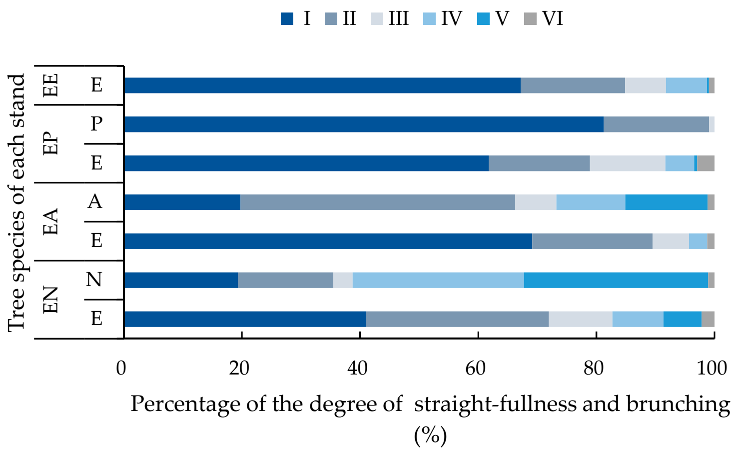


Figure 6. Degree of straight-fullness and brunching of tree stems of different tree species in each stand. Length of different colors shows the percentage of different grades of stem form. EN: mixed plantation of *Eucalyptus* (E) and *N. cadamba* (N); EA: mixed plantation of *Eucalyptus* (E) and *A. mangium* (A); EP: mixed plantation of *Eucalyptus* (E) and *P. elliottii* × *P. caribaea* (P); EE: pure forest of *E. urophylla* × *E. grandis*.

From the perspective of the whole stand, the stem structure of the trees in EN was mainly manifested as a single stem (including well-formed and slightly curved stems), and branched from the position that was higher than a third of the height of the tree (Table 6). The stem structure of the trees of EA, EP, and EE was mainly manifested as a single stem (including well-formed and slightly curved stems), with the most well-formed stems (EP > EE > EA). In short, EN had the highest ratio of branching visibly (41.0%), and EP had the most straight and complete stem form (68.7%).

Table 6. Degree of straight-fullness and brunching of tree stems among pure and mixed forests of *Eucalyptus*.

Stand Type	I (%)	II (%)	III (%)	IV (%)	V (%)	VI (%)
EN	32.3	25.0	7.8	16.8	16.4	1.7
EA	52.0	29.4	6.5	6.1	4.8	1.2
EP	68.7	17.4	8.5	3.2	0.3	1.9
EE	67.2	17.7	6.9	6.9	0.3	1.0

3.5. Degree of Stem Inclination

In the four experimental forests, more than 95% of the trees grew vertically without leaning to any side (Figure 7), except the *A. mangium* (no more than 85%), as its inclination proportion is particularly evident, up to 15.1%. The degree of inclination of *Eucalyptus* in mixed plantations was more obvious than that in the pure forest, among which EN > EA > EP. There was no inclined stem, but broken-off tree stems of *N. cadamba* at 2.2% in EN. There was a slight inclination (1.8% for Grade III, 0.9% for Grade IV) of the stems of *P. elliottii* × *P. caribaea* and 0.5% broken-off stems of *Eucalyptus* in the mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea*. As a whole, the degree of stem inclination of EA was identified to be greatest, followed by EN, EP, and EE (Table 7).

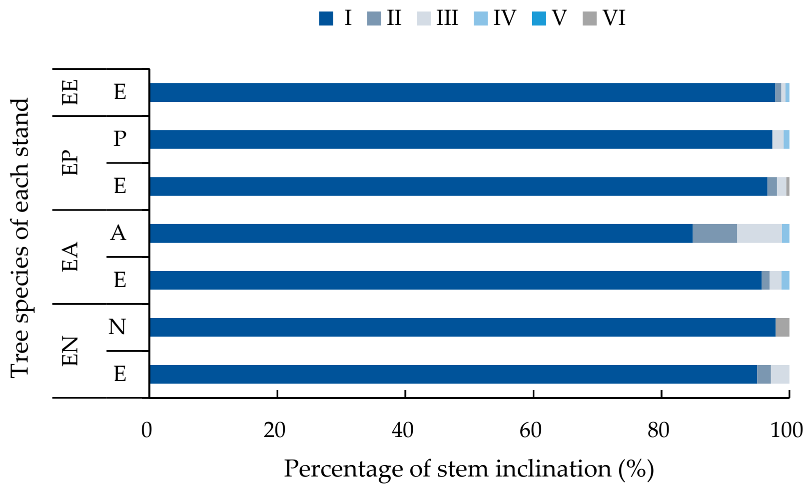


Figure 7. Degree of stem inclination of different tree species among pure and mixed forests of *Eucalyptus*. Length of different colors shows the percentage of different grades of stem inclination. EN: mixed plantation of *Eucalyptus* (E) and *N. cadamba* (N); EA: mixed plantation of *Eucalyptus* (E) and *A. mangium* (A); EP: mixed plantation of *Eucalyptus* (E) and *P. elliottii* × *P. caribaea* (P); EE: pure forest of *E. urophylla* × *E. grandis*.

Table 7. Degree of the inclination of tree stems among pure and mixed forests of *Eucalyptus*.

Stand Type	I (%)	II (%)	III (%)	IV (%)	V (%)	VI (%)
EN	96.1	1.3	1.7	0	0	0.9
EA	91.9	3.2	3.7	1.2	0	0
EP	96.8	1.0	1.6	0.3	0	0.3
EE	97.8	1.0	0.6	0.6	0	0

3.6. Evaluation of Stand Stability

The values of eight indicators of nonspatial structure were characterized and presented in Table 8. The stability of the four stands was assessed by combining the subordinate function value of the fuzzy comprehensive and the π value rule of the optimal stand state (Table 9, Figure 8). The subordinate function value of EA was 0.17 greater than the pure forest, and its state value of real stand was 0.20 greater than the pure forest. The subordinate function value of EP was 0.09 greater than the pure forest, and its state value of real stand was 0.09 greater than the pure forest. The subordinate function value of EN was 0.06 less than the pure forest, and its state value of real stand was 0.05 greater than the pure forest. Hence, the stand stability of the mixed forest of *Eucalyptus* and *A. mangium* presented as optimal for its subordinate function value of 0.76, and the state value (ω_2 = 0.61) of real stand was the largest, followed by the mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea* (ω_3 = 0.50), pure *Eucalyptus* forest (ω_4 = 0.41), and mixed forest of *Eucalyptus* and *N. cadamba* (ω_1 = 0.36).

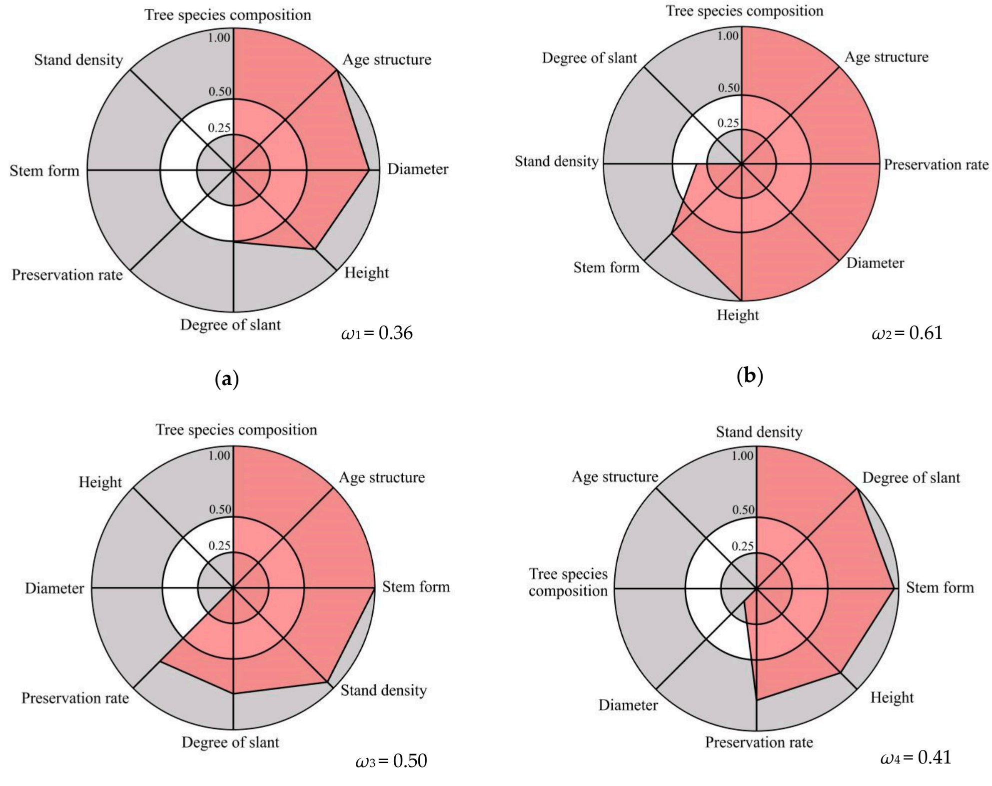
Table 8. Summary statistics of pure and mixed-*Eucalyptus* plantation.

Stand Type	Stand Density (Trees/ha)	Preservation Rate (%)	Height (m)	Diameter (cm)	Stem Form	Degree of Stem Inclination	Tree-Species Composition	Age Structure
EN	994	49.9	6.50 ± 0.12	7.29 ± 0.17	4.35 ± 0.10	5.90 ± 0.04	2	2
EA	1200	63.3	6.77 ± 0.11	7.38 ± 0.16	5.14 ± 0.08	5.86 ± 0.03	2	2
EP	1589	59.7	5.49 ± 0.13	6.12 ± 0.12	5.45 ± 0.06	5.93 ± 0.02	2	2
EE	1628	60.4	6.56 ± 0.10	6.28 ± 0.12	5.42 ± 0.06	5.96 ± 0.02	1	1

Note: The values are mean ± standard error for height, diameter, stem form, and degree of stem inclination.

Table 9. Subordinate function values of eight nonspatial structure indexes and their means of stands.

Stand Type	Stand Density	Preservation Rate	Height	Diameter	Stem Form	Degree of Stem Inclination	Tree-Species Composition	Age Structure	Subordinate Function Values
EN	0.00	0.00	0.79	0.93	0.00	0.51	1.00	1.00	0.53
EA	0.32	1.00	1.00	1.00	0.72	0.00	1.00	1.00	0.76
EP	0.94	0.73	0.00	0.00	1.00	0.75	1.00	1.00	0.68
EE	1.00	0.78	0.83	0.12	0.97	1.00	0.00	0.00	0.59



(**a**) (**b**) (**c**) (**d**)

Figure 8. Stand-state unit circles of pure and mixed-*Eucalyptus* forests of different tree species. ω_1 is the stable state value of mixed plantation of *Eucalyptus* and *N. cadamba* (EN); ω_2 is the stable state value of mixed plantation of *Eucalyptus* and *A. mangium* (EA); ω_3 is the stable state value of mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP); and ω_4 is the stable state value of the pure forest of *E. urophylla* × *E. grandis* (EE). (**a**) Mixed plantation of *Eucalyptus* and *N. cadamba* (EN); (**b**) mixed plantation of *Eucalyptus* and *A. mangium* (EA); (**c**) mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP); (**d**) pure forest of *E. urophylla* × *E. grandis* (EE).

4. Discussion

The characteristics of stand structure can express and reflect the inter- or intraspecific competition state and the stability of stands, and have great impacts on the maintenance of biodiversity, the production of target tree species, and stand qualities [35,49–51]. Stability of the forest represents the comprehensive ability of forest ecosystem to resist external environment disturbance and restore the initial state after disturbance [52,53], and ecological restoration is the fundamental measure of ecological security to maintain the relative stability of the plant ecosystem [54]. Assessing stability from the perspective of nonspatial structure can reveal its stand resistance, resilience, and durability in response to extreme climate or other natural disturbances. Building a fast-growing, high-yield, and high-stability *Eucalyptus* mixed plantation in a windy area is a way of guaranteeing protection to ensure economic benefits and improve the woodland ecological environment. Prodigious changes in nonspatial structure and stand stability of three kinds of mixed patterns of *Eucalyptus* and other tree species were demonstrated in detail, and were in line with expectations, but not all mixed patterns could improve stand stability.

4.1. Preservation Rate Changes with Mixed Tree Species

The preservation rate is not only an important indicator of the overall stability and resistance of stands, but also an important indicator of stand quality and forest health. The preservation rate reflects the internal living ability of the forest and the adaptability to the environment of the forestland, which is the quantity basis for maintaining the reasonable structure of the stand [55]. Under the condition of the same site, the stand preservation rate of each experimental forest was mainly affected by external disturbance factors or internal competition and interaction among different tree individuals in the stand. External disturbance factors mainly included human disturbance and natural disturbance. The management and tending measures of the experimental forests were all consistent except for the mixed pattern, and all stands located at the same site grew under identical climate and weather conditions, so they suffered from the same natural disturbances, especially the wind damage in the Leizhou Peninsula. Therefore, the difference in stand preservation rate was mainly affected by the mixed pattern, and the competition and interaction among different individual trees.

In our study, both *A. mangium* and *P. elliottii* × *P. caribaea* had a positive effect on the preservation of *Eucalyptus*, but only when *Eucalyptus* were mixed with *A. mangium* could the overall stand preservation rate of the mixed forest be promoted (Table 3). This is because the self-preservation rate of *P. elliottii* × *P. caribaea* was not high under the influence of *Eucalyptus* and the natural environment, so the stand preservation rate of EP was lower than that of pure *Eucalyptus*. Other studies in mixed forests of *Eucalyptus* and other tree species obtained comparable results, even though they were conducted on different mixed ratios and sites. Zheng and He demonstrated that the stand preservation rate of the mixed forest of *Eucalyptus* "Leizhou No.1" and *A. auriculiformis* mixed by row (1 row of *Eucalyptus* and 1 row of *A. auriculiformis A. Cunn.* ex Benth.) was greater than the pure forest, while that mixed by two tree individuals was lower than the pure forest [56]. Yang et al. showed that only when *Eucalyptus* "U6" and *A. crassicarpa* Benth. were mixed by ratios of 3:1 (3 rows of *Eucalyptus* and 1 row of *A. crassicarpa*) or 3:2 (3 rows of *Eucalyptus* and 2 rows of *A. crassicarpa*), their stand preservation rates were lower than the pure forest, but other mixed ratios were greater than that of the pure forest [37]. Chen indicated that the preservation rate of *E. wetarensis* Pryor × *E. camaldulensis* Dehnh. "Wc3" had increased by 1.79% after mixing with *Cunninghamia lanceolata* (Lamb.) Hook. (mixed ratio was 1 to 3) and by 1.2% after mixing with *P. massoniana* Lamb. (mixed ratio was 1 to 6) as compared with pure *Eucalyptus* forest. Meanwhile, the preservation rate of *C. lanceolata* increased, and that of *P. massoniana* decreased in the mixtures [57]. Deng also demonstrated that the stand preservation rates of the mixed forest of *E. dunnii* Maiden and *C. lanceolata* were different when they were mixed at different ratios [58]. Therefore, different mixed tree species and mixed ratios can lead to different stand preservation rates of mixed-*Eucalyptus* plantations. In addition, the preservation rate of *N. cadamba* was the highest, up to 88.9%, even though it had a negative effect on the survival of *Eucalyptus* (Table 3), which indicated that *N. cadamba* had stronger resistance than *Eucalyptus*, and *N. cadamba* may become the dominant tree species in the future. Therefore, the mixed pattern, competitive ability, and interaction among tree species under the specific sites were the main factors from which the effects will determine the future succession tendency of the community.

4.2. Mixed Pattern Affects Structure Distribution of Tree Height and Diameter

Diameter distribution and tree height distribution can reflect the degree of tree differentiation and the competition among trees in the stand, which are important indexes of the structural stability of the stand, and also important variables to measure the quality of the stand and formulate the adjustment and optimization scheme when performing management [59,60]. Diameter class structure describes the distribution characteristics of tree diameter, which can reflect the sustainability of the community to a certain extent [61]. The effect of different mixed patterns tended to be different on the diameter structure distributions in view of other scholars' studies. Yang et al. demonstrated that *Eucalyptus* "U6" of eight mixed patterns (six-year-old *Eucalyptus* mixed with *A. crassicarpa* by individual ratios of 1:1, 2:1, 3:1, and 3:2, and by row ratios of 1:1, 2:1, 3:1, and 3:2) had a larger proportion of diameter class above 15 cm than pure *Eucalyptus* forest, and the maximum over 30.0% only when *Eucalyptus* was mixed with *A. crassicarpa* by individual (1 individual of *Eucalyptus* and 1 individual of *A. crassicarpa*) and by row (1 row of *Eucalyptus* and 1 row of *A. crassicarpa*) [37]. Zhao's study showed that whether *E. urophylla* × *E. grandis* or *Styrax tonkinensis* (Pierre) Craib ex Hartw. was used for mixed forest, the proportion of wood of larger than 12 cm diameter was more than their respective pure stands [62]. Yang showed that the proportion of trees whose DBH was less than the average DBH in the mixed forest of *E. urophylla* × *E. grandis* and *Castanopsis fissa* (Champion ex Bentham) Rehder et E. H. Wilson was less than that in the pure forest, which is quite beneficial to the cultivation of large-diameter *Eucalyptus* [60]. In our study, *Eucalyptus* showed evident advantages of fast growth on height by comparing the growth rate of mixed tree species so that all the mixed plantations had a lower proportions of trees with tree height class greater than 7 m than the pure forest (Table 4, Figure 4), which showed that the competition for resources among trees in pure *Eucalyptus* forests was greater than that in mixed forests. Generally, broad-leaved forest stands with complex structure and high species diversity have more advantages in resisting disturbance, self-regulation, maintaining stability, and exerting ecological benefits than pure forests of the same age [63]. Therefore, the results of our study that the proportion of trees with a height class more than 7 m was EE > EA > EN > EP and the proportion of trees with diameter class above 7 cm was EA > EN > EE > EP indicated that the stand resistance and resilience of the mixed forest of *Eucalyptus* and *A. mangium* (EA) were the strongest in response to external disturbances, which is consistent with the assessment of stability (Tables 4 and 5, Figure 8).

4.3. Stem Form and Status of Stem Affects Stand Quality

The shape of stem growth is generally called stem form. An excellent stem form can not only improve the growth of trees, but also the wood quality [64,65]. The stem form and morphology of stem are often included in the selection index when people carry out the process of superior tree selection [66,67], and the structure and status of stem are often the most important observable indicators in the study of the resistance of stand response to natural disturbance factors such as wind, ice, and rainfall [42,68]. Therefore, the structure of the stem form of a stand can assess the overall stand resistance and present stand quality effectively. Windstorms constantly occur and land in southern China [69–71], and extreme windstorms manifest almost every year on the Leizhou Peninsula, Zhanjiang City [39], which leads to a general concern and numerous studies on wind resistance. The results of the research on the mixed forest of *Eucalyptus grandis* × *E. urophylla* and *Casuarina equisetifolia* Forst. were a little different from ours, in that they concluded that not only *Eucalyptus* in two ratios of mixtures (3:2 and 4:1), but also the whole mixtures, suffered less wind damage than *Eucalyptus* pure forest after being hit by typhoon "Vicente" (STY, wind force $\geq$ 45 m/s), during which wind fall was the main damage to *Eucalyptus* in mixtures, and branches or stems broken were mostly in pure forest [72]. Hence, the wind resistance varied enormously with different *Eucalyptus* clones [42,73] with mixed ratio and mixed tree species. The distribution structure on the degree of straight-fullness and brunching and stem inclination clearly demonstrated that most of the tree individuals presented a single stem, vertical growth, and no inclination of the stem regardless of whether it was a mixed forest or a pure forest (Tables 6 and 7), which is basically identical to their status under natural growth condition [74–77]. However, the integral stand-stem form of the mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP) was more straight and complete under the same site quality, since *P. elliottii* × *P. caribaea* had little impact on *Eucalyptus* trees due to its slow growth, and suffered less wind resistance compared to the other two broad-leaf species. The mixed forest of *Eucalyptus* and *A. mangium* had a higher ratio of inclined stems, and the mixed forest of *Eucalyptus* and *N. cadamba* had a higher ratio of tree branching stems. According to previous studies, the wind resistance was proved to be *P. elliottii* × *P. caribaea* > *A. mangium* > *Eucalyptus urophylla* × *E. grandis* from high to low in sequence after suffering the typhoon "Mujigae" [78], and the wind resistance of *N. cadamba* was better than *A. mangium* [79]. Therefore, there may be some mechanisms of interaction existing in tree individuals. Generally, the tree individuals may secrete some chemical substances to interfere with each other in the process of growth to compete for more resources in a limited space or resist external disturbance [80]. Such allelopathic mechanisms of interaction and growth mechanisms adapting to the environment are still worth further study.

4.4. Limitations

The row spacing was treated differently when planting these experimental forests, in view of the differences in canopy morphology of each tree species and the demand for space resources. Nevertheless, the size of row spacing and the stand density can influence the growth of stand, so stand density was also considered an important indicator when assessing the stand quality and stability. However, whether there is a better density and row spacing to make the stand structure more stable remains to be further studied. In addition, the structural characteristics of the shape of crown, the distribution of branches and roots, species diversity, and distribution in the forest may affect the stability and stress resistance of the stand, which is also worth further study.

5. Conclusions

Assessing the stand stability of pure and mixed-*Eucalyptus* forests in typhoon-prone areas is critical for choosing appropriate mixed patterns and species. In this study, we found that the overall stand preservation rate of the mixed forest can be promoted when *Eucalyptus* were mixed with *A. mangium*. The height of EN and EP, as well as the diameter of EP, distributed at a lower level than that of the pure *Eucalyptus* plantation, and the height of EP appeared to have a two-peak distribution. The stem of EN was testified to be more curving and brunching than that of the pure *Eucalyptus* plantation, the stem of EA was testified to be more curving and inclined than that of the pure *Eucalyptus* plantation, and the stem of EP was testified to grow straightly. Only *A. mangium* can markedly advance the stand stability of *Eucalyptus* plantations; *P. elliottii* × *P. caribaea* can improve the stand stability of *Eucalyptus* plantations mildly, and *N. cadamba* is not conducive to the stand stability of *Eucalyptus* plantations. To sum up, *A. mangium* is a superior tree species to mix with *Eucalyptus* for a more stable stand structure in windy areas to approach an evident and immense stability and resistance in response to extreme climate, followed by *P. elliottii* × *P. caribaea* and *N. cadamba*, which is of great significance to renovate inefficient *Eucalyptus* plantations and restore forest ecology.

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