Stand Stability of Pure and Mixed Eucalyptus Forests of Different tree Species in a Typhoon-prone Area

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Research

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Abstract

Background: Stable stand structure of mixed plantations is the basis of giving full play to forest ecological function and benefit, and the pure *Eucalyptus* plantations with large-area and successive planting have presented to be unstable and vulnerable in typhoon-prone area. In this study, we investigated eight 30 m × 30 m plots randomly in pure and mixed eucalyptus forests on growth status, characterized and compared the distribution of non-spatial structure of mixtures with that of mono-species plantation, and evaluated the stand quality and stability from eight indexes including preservation rate, stand density, height, diameter, stem form, degree of slant, tree species composition and age structure, so as to find out the best mixed composition and pattern of eucalyptus and other tree species in typhoon-prone area.

Results: *Eucalyptus* surviving in the mixed forest of *Eucalyptus* and *A. mangium* (EA) and the mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP) were 5.0% and 7.6% greater than those in pure *Eucalyptus* forest (E) respectively, while only the stand preservation rate of EA was greater (+2.9%) than that of pure *Eucalyptus* forest. The proportions of all mixtures on the height class that greater than 7 m were fewer

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than that of monoculture. The proportion of EA and EN (mixed forest of *Eucalyptus* and *N.cadamba*) on the diameter class that greater than 7 m were 10.6% and 7.8% respectively more than that of monoculture. EN got a highest ratio of branching visibly (41%), EA got a highest ratio of slant stems (8.1%) and EP got a most straight and complete stem form (68.7%). The stand stability of the mixed forest of *Eucalyptus* and *A. mangium* presents to be optimal for its subordinate function value (0.76) and status value (ω = 0.607) of real stand were the largest.

Conclusion: *A. mangium* is a most superior tree specie 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 on the forest management.

Keywords: Mixed forest, Preservation rate, Stability, Stem form, Non-spatial structure

Background

As a fast-growing tree species, *Eucalyptus* have been introducing and promoting genetic improvement in many regions to produce large amounts of wood for economic development (Zhou et al. 2020). But large-area planting and continuous-planting rotation of commercial *Eucalyptus* plantations have caused various problems such as reduced species diversity, loss of soil nutrients, which threatens ecological and timber security regionally and worldwide (Wen et al. 2005; Ye et al. 2010; He 2019; Zhu et al. 2019; Zhou et al. 2020). Constructing the mixed forests can form stratified stand structure, which helps to make full use of forest land space and environmental resources, increase the light energy utilization, regulate the climatic environment within and outside the forest, improve forest land environment, so as to improve forest productivity, increase species diversity, enhance the forests ability to resist the disaster, exert forest ecological protection benefits, promote the ecological balance (Le Maire et al. 2013; Santos et al. 2017; Liu et al. 2018). So it is necessary to choose suitable and superior tree species to build high quality *Eucalyptus* mixed plantation. Nevertheless, the growth of mixed plantation is mainly restricted by the choice of the site and tree species, the collocation of row spacing, the mixing proportion and pattern. In view of the complexity of these factors, it is still rough to mix different tree species with *Eucalyptus* in line with expectations and to ensure the ecological and economic benefit and realize sustainable development of *Eucalyptus* plantation.

The research on *Eucalyptus* mixed plantations have got under way for nearly 43 years since J.J. Burdon and G.A. Chilvers did preliminary studies on a native Australia *Eucalyptus* forest invaded by exotic *Pinus radiata* in 1977 (Burdon and Chilvers 1977), and few years later rigorous research had been done on mixed-species plantations of *Eucalyptus* and other tree species with scientific experimental design at one site (Chu et al. 1981; He et al. 1988; Kelty 2006). Later, other scholars also did a lot of researches on mixed *Eucalyptus* plantation,but most studies on *Eucalyptus* mixed plantation focused on water use (Forrester et al. 2010), light use (Le Maire et al. 2013), carbon allocation (Forrester et al. 2006; Nouvellon et al. 2012; Huang 2013; Wen et al. 2020; Zhang 2020), productivity (Forrester et al. 2007; Nouvellon et al. 2012; He 2019), nutrient cycle (Santos et al. 2017; Voigtlaender et al. 2019; Yao et al. 2019; Zhang et al. 2021), microbial communities (Huang et al. 2017; Pereira et al. 2019) or succession dynamics (Forrester et al. 2004; Santos et al. 2016) and less research had been done on the structural features of mixed *Eucalyptus* plantation.

Forest structure determines the service function of forest ecosystem by influencing forest environment and biological factors (Gong et al. 2012). A reasonable stand structure is not only the basis of giving full play to forest function and benefit (Kong 2013) but also the main driving force of forest ecosystem succession. The study on stand structure is the theoretical basis of forest management and analysis and the comprehensive reflection of stand development process such as tree species competition, natural succession and disturbance activities (Jiang 2015).

The stand structure includes spatial structure and non-spatial structure. 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. Non-spatial structure, 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 (Gadow et al. 2012; Hui 2013; Li et al. 2016; Zhu 2016; Wei et al. 2019), 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. Peng Shaolin 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 (Peng 1987). 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 (O 'Connor et al. 2017). Through the study on the structure of stand, we can understand their distribution rules and the interaction relationship between tree species (Kong 2013),so as 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 is improved and change greatly, the stand stability and stress resistance on resisting external adverse disturbance is enhanced tremendously, indicating the correct selection of mixed species and the success of mixed pattern. In windy areas, the 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 (Yang et al. 2009). Therefore it is of great significance to study the stand structure of *Eucalyptus* plantation mixed with different trees species, especially the *Eucalyptus* plantation in windy areas.

Taken the preservation rate, stand density, height, diameter, the stem form, the degree of slant, tree species composition and age structure as evaluation indexes of the non-spatial structure, this paper aims to analyze the structure difference on *Eucalyptus* plantation of monoculture and mixtures that mixed respectively with three different tree species (*Neolamarckia cadamba*, *Acacia mangium* and *Pinus elliottii* × *P. caribaea*), embarking from the actual growth status of each plantation, to explore the stand stability and resistance of the monoculture and mixtures of eucalyptus forests and find out the best composition and pattern of eucalyptus mixed with tree species in typhoon-prone area.

Material and methods

Site characteristics

The experimental field was located in Leizhou Peninsula in Jijia Town, Zhanjiang City, Guangdong Province (20º 26' - 21º 11' N, 109º 42' - 110º 23' E) of , with an elevation of 35 m and a gentle terrain of nearly 0º slope. The region is dominated by humid monsoon climate of tropics with a mean annual temperature of 23.5 ºC, a mean annual precipitation of 1855 mm, a mean annual evaporation capacity of

1762.9 mm, and a relative humidity of 82-84%, presenting an obvious dry and wet season (May - September - rainy season, with south wind blowing mainly, and November - next April - dry season, with north wind blowing mainly). Frequent tropical storms or typhoons lands in Leizhou Peninsula for 1 - 3 times every year, which is the primary natural calamities in Leizhou Peninsula.

Characteristics of the experimental plantations

These experimental plantations were constructed in February 2014, including one pure plantation of *Eucalyptus urophylla* × *E. grandis* 'DH32-29' (E) as control and three mixed *Eucalyptus* (DH32-29) plantations that mixed with three kinds of tree species respectively: (1) Mixed plantation of *Eucalyptus* and *Neolamarckia cadamba* (EN) was mixed by strips for four rows of *Eucalyptus* and four rows of *N. cadamba*; (2) Mixed plantation of *Eucalyptus* and *Acacia mangium* (EA) was mixed by strips for four rows of *Eucalyptus* and four rows of *A. mangium*; (3) Mixed plantation of *Eucalyptus* and *Pinus elliottii* × *P. caribaea* (EP) was mixed by rows for one row of *Eucalyptus* and one row of *P. elliottii* × *P. caribaea.* Since the biological characteristics of different tree species are different intrinsically, *Eucalyptus* 'DH32-29' and *P. elliottii* × *P. caribaea* were planted at spacing of 1.3 m ×3.0 m, *N. cadamba* was planted at spacing of 3.9 m ×3.0 m, and *A. mangium* was planted at spacing of 2.6 m ×3.0 m. They are all fast growing excellent tree species with strong adaptability to grow in Leizhou Peninsula, However, They were damaged by severe wind damage every year after planted (See Table 1 for details). Due to the catastrophic damage of typhoon "Mujigae"(Super Typhoon, Wind force ≥ 51.0m /s, Beaufort scale ≥ 16) in October 2015, all *Eucalyptus* trees were blown down with stems broken, hence all *Eucalyptus* were cut off from basal stem to facilitate new branches germinated and renew the whole stands. Recover measures that erecting leaning or fallen trees were taken for mixed species to restore stands. In June 2016, one strong branch of each individual of *Eucalyptus* was preserved and the others were cut off. Other tending measures were consistent across the four stands.

Table 1 Appearance situation of tropical cyclones in Leizhou Peninsula from 2014 to 2017

Landing date	Suffering time	Name	Number code	Maximum wind speed at landfall (m/s)	Beaufort scale	Intensity rank

July 18, 2014	7:30 p.m.	Rammasun	1409	60/72	17	Super Typhoon (SuperTY)
September 16, 2014	9:40 a.m.	Kalmaegi	1415	42	13	Severe Typhoon (STY)
October 4, 2015	2:10 p.m.	Mujigae	1522	50/52	15/16	SuperTyphoon (SuperTY)
August 18, 2016	3:40 p.m.	Dianmu	1608	20/28	8	Tropical storm (TS)

Data measurements

By the end of April 2017, two 30 m × 30 m plots were set randomly in each mixed *Eucalyptus* forest (including three mixed stands and one pure stand) adopting the random sampling method to measure the height, the diameter, the straight-fullness and brunching status of stem form, the slant of stem of each tree individual and record the number of preserved and missing trees. The height (H, unit: m) was measured with a laser altimeter (Nikon Rangefinder Rieho 1000AS) (precision: 0.1 m). When the diameter at breast height (DBH) of an individual tree was less than 4 cm, the groud diameter (unit: cm) was measured with a vernier caliper, otherwise 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 slant of each individual were evaluated by the classification methods as Table 2 for statistics.

Table 2 Classification criteria of tree stem form

Stem form		**Degree of slant**	
Classification	**description**	**Classification**	**description**
I	The tree has one single stem that is complete and straight (well-formed).	I	The tree stem grow vertically without lean to any side.
II	The tree has one single stem that is complete and curved slightly.	II	The tree stem has 0° to 30° oblique.
III	The tree has more than two stems that are branched below a third of its height.	III	The tree stem has 30° to 60° oblique.
IV	The tree has more than two stems that are	IV	The tree stem has 30° to 60° oblique.

	branched higher than one third and lower than two thirds of its height.		
Ⅴ	The tree has more than two stems that are branched higher than two thirds of its height.	Ⅴ	The treetop was broken off.
Ⅵ	The tree has one single stem that is bent badly.	Ⅵ	The tree stem was broken off.

Data Processing and Statistical Analysis

Eight indicators of non-spacial structure were assigned as preservation rate, stand density, height, diameter, stem form, degree of slant, tree species composition and age structure.

Preservation rate = Number of retained plants/number of planted plants ×100%.

The tree height distribution was calculated by using the tree height class integration method: every two 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 two 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 slant status of stem were analyzed through their classification.

Two tree species and two ages exist in the mixed forests, one tree species and one age exist in the pure forests, hence the tree structure and age structure of the mixed forest were assigned a value of while that of the pure forest was assigned a value of 1. Other evaluation indexes were assigned as their average values when evaluated. The values of stability indexes were standardized firstly adopting the method of subordinate function value of fuzzy mathematics (Guo et al. 2009; Yu et al. 2015; Yang et al. 2020) and forward to make it dimensionless between [0,1]. The formula is as follows:

$$U_{ij} = \frac{(x_{ij} - x_{i\min})}{(x_{i\max} - x_{i\min})} \tag{1}$$

Where U_{ij} is the subordinate function value of i indexes of j stand, and $U_{ik} \in [0,1]$. x_{ij} is the measured value of i indicator of j stand, $x_{i\min}$ is the minimum value of i indexes of j stand and $x_{i\max}$ is the maximum value of i indicator of j stand.

The stability of four *Eucalyptus* forests were assessed by the method of π value rule of optimal stand state (Hui et al. 2016; Wan et al. 2020). The methods are as follows: Draw a circle with a radius of 1 and divide the circle of 360° into 8 sector areas which representing eight non-spatial 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; Mark the corresponding index value of each stand on the radiation with points, connect adjacent points in turn to form a closed curve, which represents the stability status of the real stand.

When all indicators equal to one, the maximum circular area of π can be regarded as 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:

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

$$\omega = \frac{s_2}{\pi} = \frac{\sum_{i=1}^{n} s_{2i}}{\pi}, \ \mathrm{m} = 0 \tag{3}$$

$$s_{2i} = \frac{\sin\theta}{2} L_1 L_2 \tag{4}$$

Where ω is stable degree of the status 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 that equal to 1; L_1 and L_2 are values of two adjacent indicator in the triangle part respectively; θ is the angle formed by two adjacent indicators.

Therein, $\omega \in [0,1]$. It indicates excellent status when $\omega \geq 0.70$; It indicates a good status when $\omega \in [0.55, 0.70]$; It indicates a general status when $\omega \in [0.40, 0.55)$; It indicates a poor status when $\omega \in [0.25, 0.40)$; It indicates a very terrible status when $\omega \leq 0.25$.

Microsoft Excel 2007 was used for data processing, R x64 3.5.1 was used for data analysis, and Python 3.8 was used for drawing Fig. 5.

Results

Preservation of *Eucalyptus* pure and mixed plantation

The preservation rates varies in tree species and stands 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 pure *Eucalyptus* forest (E) respectively,while *Eucalyptus* surviving in EN mixture was 18.8% fewer than those in pure *Eucalyptus* forest (E). So 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 for 88.9%, *A. mangium* survived for 59.3% and *P. elliottii* × *P. caribaea* survived the fewest for 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%) since experiencing severe wind damage for four times, and only the preservation rate of EA was 2.9% greater than that of pure *Eucalyptus* plantation.

Table 3 Preservation rate of pure and mixed *Eucalyptus* plantation (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
E	60.4	—	60.4

The number in Table 3 is the percentage of the preservation rate of *Eucalyptus*, mixed species or the entire stand.

Tree height distribution

The distribution pattern of tree height structures of 18-month-old *Eucalyptus* was demonstrated to be similar in pure *Eucalyptus* forest and mixed *Eucalyptus* forest (Fig. 1). The tree height class of 7 m got 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. While 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 uneven aged multistoried structure obviously (Fig. 1).

Regarding the four forests of pure *Eucalyptus* and mixtures, the tree heights of EA were mainly distributed from 6 to 10 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 pure *Eucalyptus* forest (Table 4). However, the tree heights of EN and EP were lower than that of pure *Eucalyptus* forest in that tree heights of EN were mainly distributed from 4 to 8 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 to 4 m (31.3%) and 6 to 8 m (39.0%). Ultimately, even though the proportion of height class that greater than 7 m of *Eucalyptus* was EA> EP > E > EN from high to low in sequence, the proportion of height class that greater than 7 m in EA was similar to pure *Eucalyptus* plantation (0.3% less), and that in EN and EP were 6.9%, 23.5% respectively less than that in pure *Eucalyptus* plantation (Table 4).

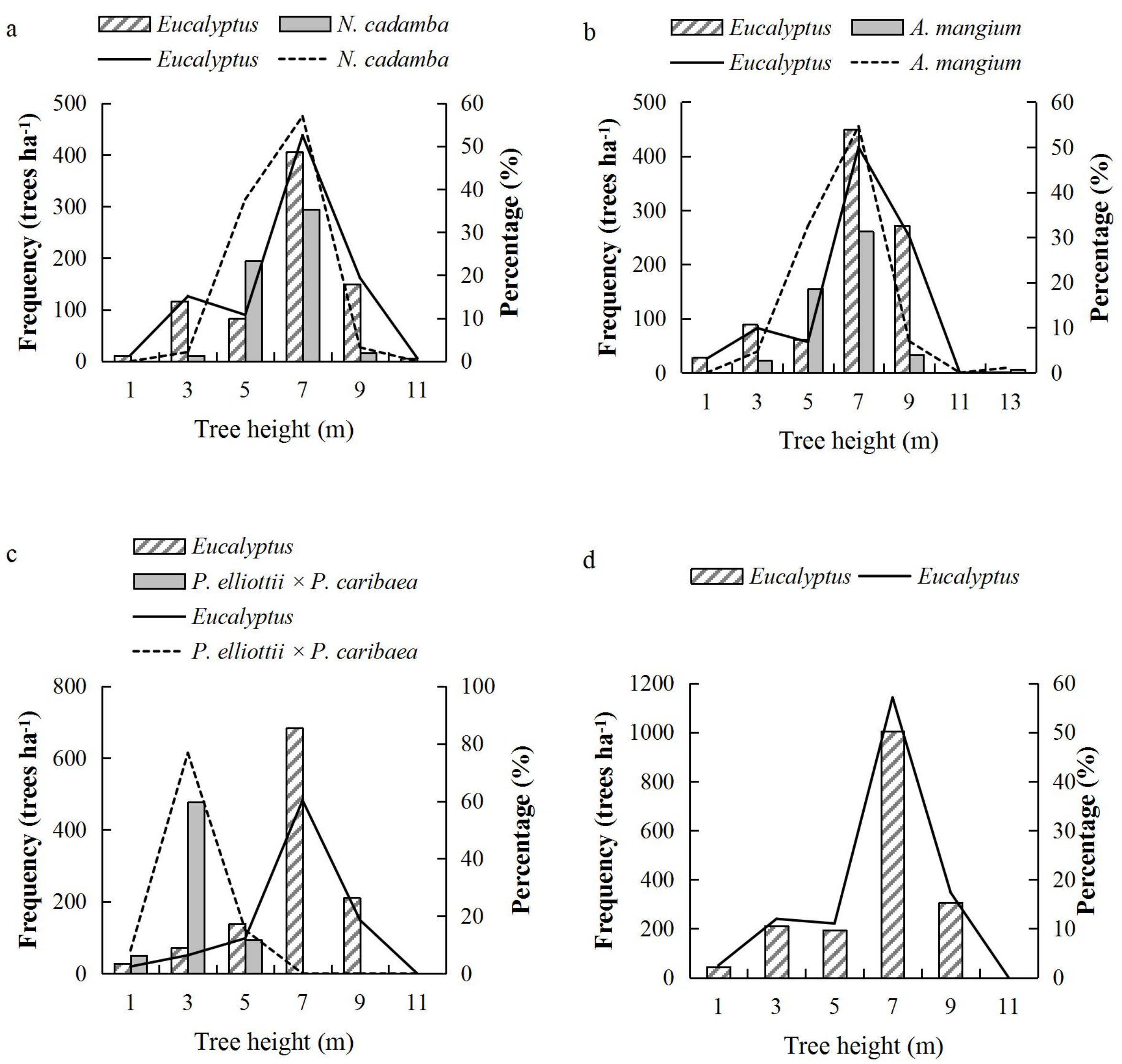

Fig. 1 Tree height distribution of *E. urophylla* × *E. grandis* at the age of 18 months and of mixed tree specie at the age of 38 months in monocultures and mixtures. Height of the histograms show the distribution frequency of tree height of each tree species per hectare. The line show the distribution 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* (E).

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

Stand type	1		3		5		7		9		11		13	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
EN	11	0.9	128	9.9	283	21.6	689	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
E	44	2.5	211	12.0	194	11.0	1006	57.1	306	17.4	0	0	0	0

Diameter distribution

The diameter distribution of *Eucalyptus* in the different mixtures resembles that of pure forest: the diameter class of 7 cm accounted for the largest proportion, followed by 9 cm diameter class, in spite that some subtle differences were demonstrated among the four stands (Fig. 2). With regard to mixed tree species, both the diameter class distribution of *N. cadamba* and *A. mangium* were exhibited to be two peak structure and ranged from 5 to 11 cm mostly, while most diameter of *P. elliottii* × *P. caribaea* ranged from 3 to 7 cm. The proportion of diameter class that greater than 7 cm of *Eucalyptus* from high to low was EP > EA >EN >E, and that of mixed species from high to low was *A. mangium*, *N. cadamba* and *P. elliottii* × *P. caribaea*.

It is demonstrated (Table 5) that the distribution of stand diameters of EN and EA were identical to pure *Eucalyptus* forest for diameters was mainly distributed in 7 cm diameter class (ranged from 6 to 8 cm), followed by 9 cm diameter class (ranged from 8 to 10 cm). The diameter of mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea* were mainly distributed in diameter class of 7 cm (33.6% ranged from 4 to 6 cm), followed by 5 cm diameter class (25.6% ranged from 4 to 6 cm). Generally, the proportion of diameter class that greater than 7 cm of stands was EA> EN>E>EP from high to low (Table 5).

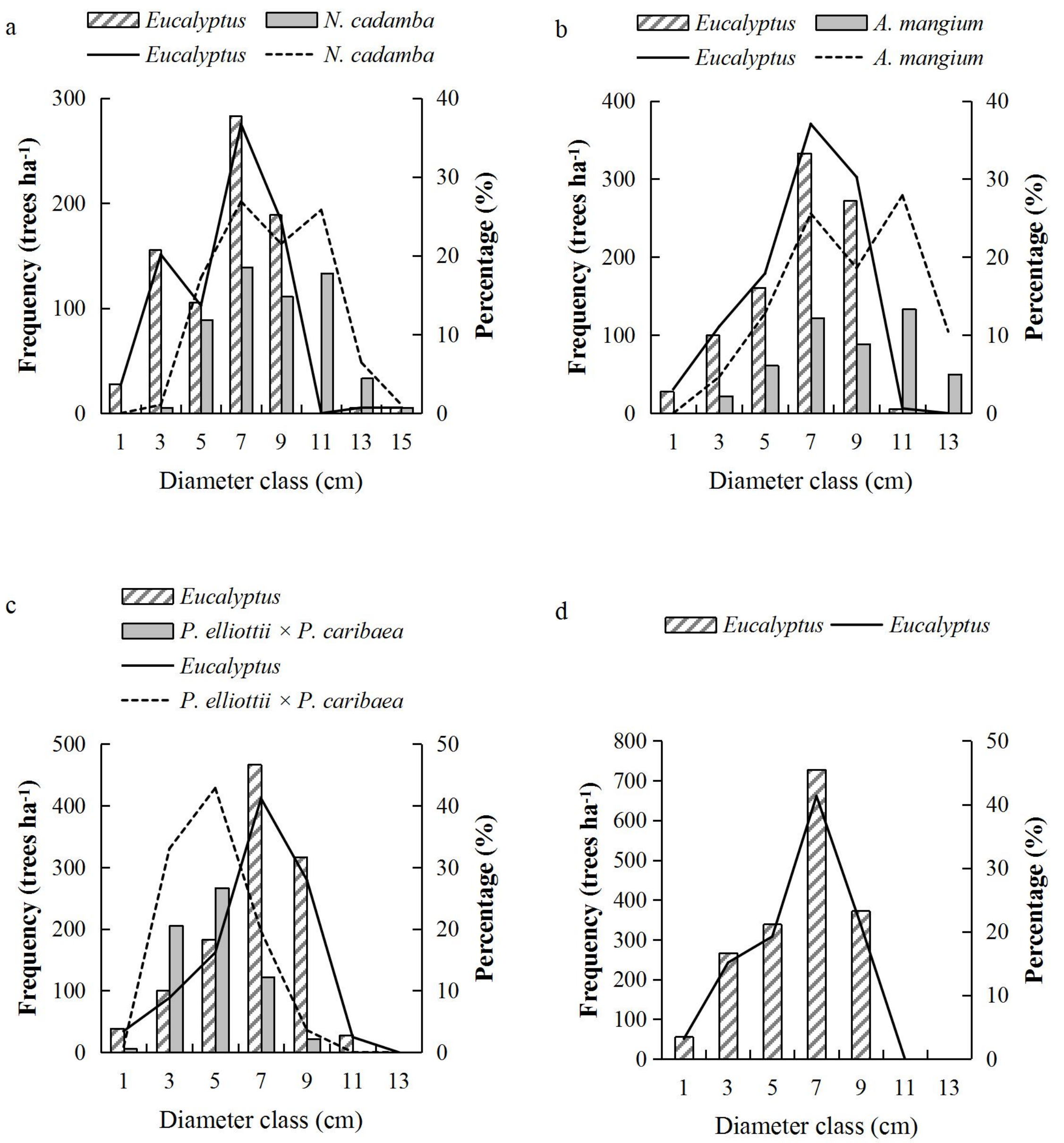

Fig. 2 Diameter distribution of *E. urophylla* × *E. grandis* at the age of 18 months and of mixed tree specie at the age of 38 months in monocultures and mixtures. Height of the histograms show the distribution frequency of diameter of each tree species per hectare. The line show the distribution percentage 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* (E).

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

Stand type	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
E	55	3.1	267	15.2	339	19.3	728	41.3	372	21.1	0	0.0	0	0	0	0

Structure of the tree stem form

Apparent differences on the degree of straight-fullness and brunching were demonstrated in Fig.3. In different mixed patterns, only the proportion of straight-fullness of *Eucalyptus* stems in EA was larger than that in pure forests (1.9% larger in Grade I), and the proportion of branches was lower than that in pure forests (0.7% lower in Grade III, 3.8% lower in Grade IV and 0.3% lower in Grade V). The proportion of Grade I of *Eucalyptus* stems in EN were 26.2% lower than that in pure forests, and the proportion of Grade III, Grade IV and Grade V of *Eucalyptus* stems were respectively 3.9 %, 1.7%, 6.2% greater than that in pure *Eucalyptus* forest. The stem straight-fullness proportion of *Eucalyptus* in EP was slightly lower than that of pure *Eucalyptus* forest, and the branches were slightly more than that of pure *Eucalyptus* forest.

Compared to other mixed species, the degree of straight-fullness and brunching of tree stems of *N. cadamba* on Grade I and Grade II accounted for the least proportion of 19.4% and 16.1 %, and on Grade IV and Grade V accounted for the largest proportion of 29.0% and 31.2 %, indicating that branches of most *N. cadamba* sprouted from the position that greater than a third of the height of the tree. Most of *A. mangium* mainly got 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 accounts for 81.3%.

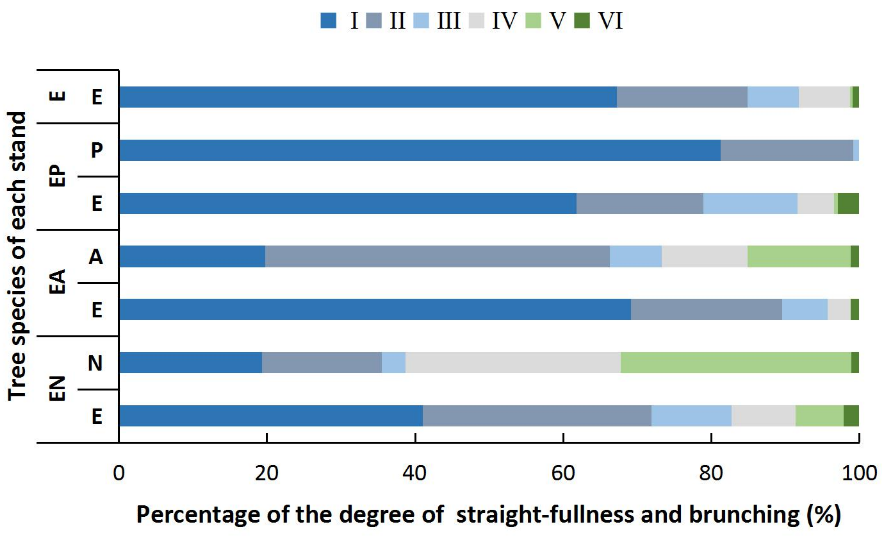

Fig. 3 Degree of straight-fullness and brunching of tree stems of different tree species in each stand. Length of different colors show the percentage of different grades of stem form. EN: Mixed plantation of *Eucalyptus* (E) and *N. cadamba* (N); EA: Mixed plantation of *Eucalyptus* (E) and *A. mangium* (A); EP: Mixed plantation of *Eucalyptus* (E) and *P. elliottii* × *P. caribaea* (P); E: Pure forest of *E. urophylla* × *E. grandis* (E).

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 higher than a third of the height of the tree (Table 6). The stem structure of the trees of EA, EP and E was mainly manifested as a single stem (including well-formed and slightly curved stems), with the most well-formed stems (EP>E>EA). In short, EN got a highest ratio of branching visibly (41%) and EP got a 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
E	67.2	17.7	6.9	6.9	0.3	1.0

Degree of stem slant

In the four experimental forests, more than 95% of the trees grew vertically without lean to any side (Fig. 4), except the *A. mangium* (no more than 85%) for its slant proportion is particularly evident that up to 15.1%. The slant degree of *Eucalyptus* in mixed plantations were more obvious than that in pure forest, among which EN > EA > EP. There was no slanting stem but 2.2% broken-off tree stems of *N. cadamba* in EN. There was a slight slant (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 slant of EA was identified to be greatest, followed by EN, EP and E.

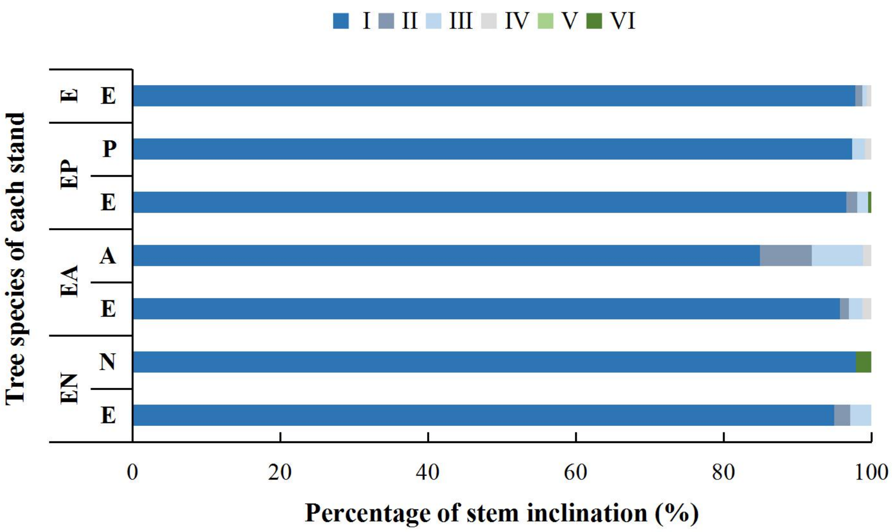

Fig. 4 Degree of stem slant of different tree species among pure and mixed forests of *Eucalyptus*. Length of different colors show the percentage of different grades of stem slant. EN: Mixed plantation of *Eucalyptus* (E) and *N. cadamba* (N); EA: Mixed plantation of *Eucalyptus* (E) and *A. mangium* (A); EP: Mixed plantation of *Eucalyptus* (E) and *P. elliottii* × *P. caribaea* (P); E: Pure forest of *E. urophylla* × *E. grandis* (E).

Table 7 Degree of the slant 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
E	97.8	1.0	0.6	0.6	0	0

Evaluation of stand stability

Four stands' stability were assessed by combining with the Subordinate function value of fuzzy comprehensive and the π value rule of optimal stand state (Table 8, Fig. 5). The subordinate function value of EA is 0.17 greater than pure forest and its status value of real stand is 0.198 greater than pure forest. The subordinate function value of EP is 0.09 greater than pure forest and its status value of real stand is 0.087 greater than pure forest. The subordinate function value of EA is 0.06 less than pure forest and its status value of real stand is 0.053 greater than pure forest. Hence the stand stability of the mixed forest of *Eucalyptus* and *A. mangium* presents to be optimal for its subordinate function value of 0.76 and status value (ω_2 = 0.607) of real stand are the largest, followed by mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea* (ω_3 = 0.496), pure *Eucalyptus* forest (ω_4 = 0.409) and mixed forest of *Eucalyptus* and *N. cadamba* (ω_1 = 0.356).

Table 8 Subordinate function values of eight non-spatial structure indices and their means of stands

Stand type	Stand density	Preservation rate	Diameter	Height	Stem form	Degree of slant	Tree species composition	Age structure	Subordinate function values
EN	0.00	0.00	0.93	0.79	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
E	1.00	0.78	0.12	0.83	0.97	1.00	0.00	0.00	0.59

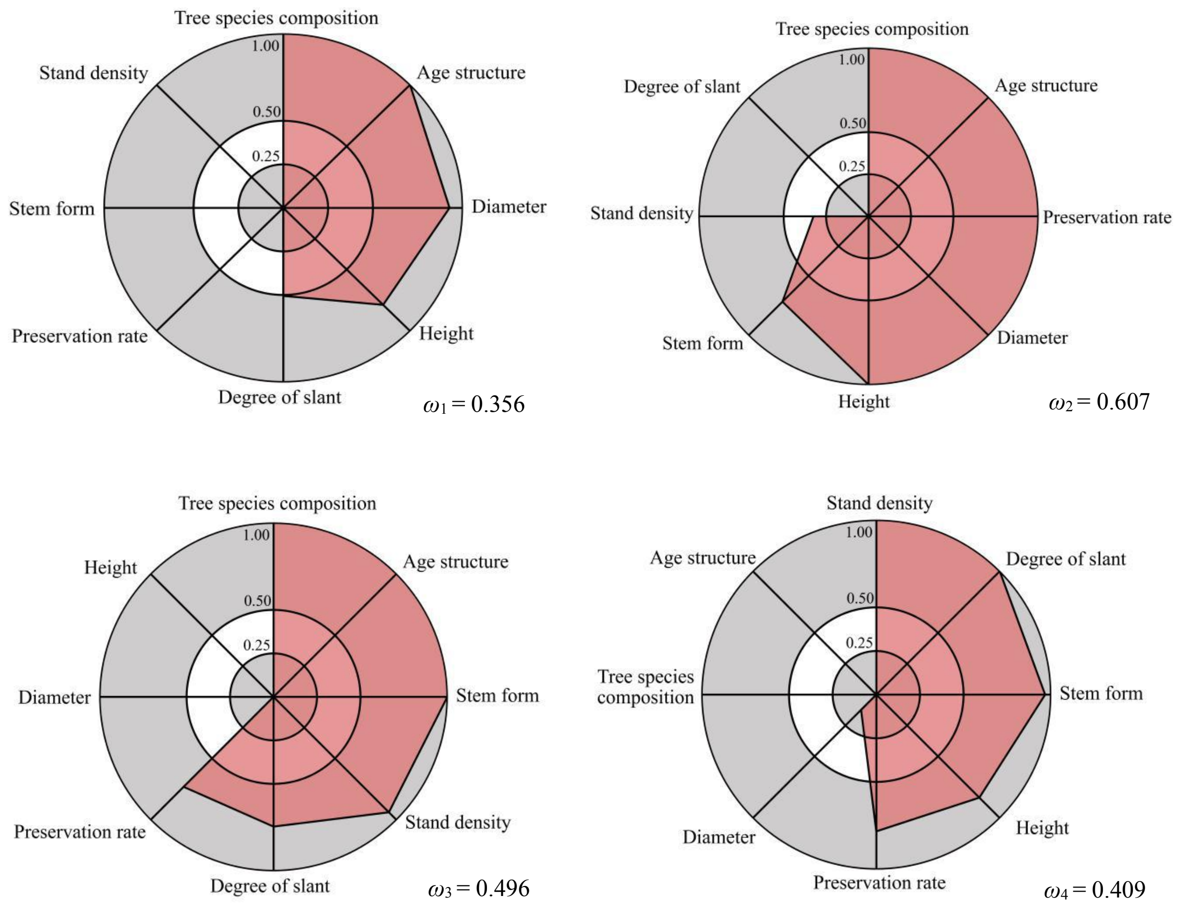

Fig. 5 Stand state unit circles of pure and mixed *Eucalyptus* forests of different tree species. ω_1 is the stable status value of mixed plantation of *Eucalyptus* and *N. cadamba* (EN); ω_2 is the stable status value of mixed plantation of *Eucalyptus* and *A. mangium* (EA); ω_3 is the stable status value of mixed plantation of *Eucalyptus* and *P. elliottii* × *P. caribaea* (EP); ω_4 is the stable status value of pure forest of *E. urophylla* × *E. grandis* (E).

Discussion

The characteristics of stand structure can express and reflect the competition status inter- or intra-specific and the stability of stands, which have great impacts on the maintenance of biodiversity, the production of target tree species and stand qualities. Stability of forest represents the comprehensive ability of forest ecosystem to resist external environment disturbance and restore the initial state after disturbance (Ma and Li 2004), and ecological restoration is the fundamental measure of ecological security to maintain the relative stability of plant ecosystem. Assessing stability from the perspective of non-spatial structure can reveal its stand resistance, resilience and durability in response to extreme climate or other natural disturbances. Building a fast-growing, high-quality and high-stability *Eucalyptus* mixed plantation in windy area is a way of guarantee and protection to ensure economic benefits and improve woodland ecological environment. Prodigious changes on non-spatial structure and stand stability of three kinds of mixed patterns of *Eucalyptus* and other tree species were demonstrated with detail which are in line with expectations, but not all mixed patterns can improve stand stability.

Preservation rate changes with mixed tree species

The preservation rate is not only an important indicator of the overall stability and resistance of stand, 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 (Xing 2013). Under the condition of the same site, the stand preservation rate of each experimental forest was mainly affected by external interference factors or internal competition and interaction among different tree individuals in the stand. External interference factors mainly include 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 the identical climate and weather condition so they suffered from the same natural disturbance especially the wind damage in Leizhou Peninsula. Therefore, the difference of stand preservation rate is 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* have a positive effect on the preservation of *Eucalyptus*, but only when *Eucalyptus* were mixed with *A. mangium*, the overall stand preservation rate of the mixed forest can 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 natural environment so that 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 ratio and sites. Zheng and He had demonstrated that the stand preservation rate of mixed forest of *Eucalyptus* 'Leizhou No.1' and *A. auriculiformis* mixed by rows (1 row of *Eucalyptus* and 1 row of *A. auriculiformis*) was greater than pure forest while that mixed by two tree individuals was lower than pure forest (Zheng and He 1992). Yang et al. showed that only when *Eucalyptus* 'U6' and *A. crassicarpa* 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 pure forest but other mixed ratios were greater than that of pure forest (Yang et al. 2009). Chen indicated that the preservation rate of *E. wetarensis* × *E. Camaldulensis* 'Wc3' had increased by 1.79% after mixed with *Cunninghamia lanceolata* (mixed ratio was 1 to 3) and by 1.2% after mixed with *P. massoniana* (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 (Chen 2016). Deng also demonstrated that the stand preservation rates of mixed forest of *E. dunnii* and *C. lanceolata* were different when they were mixed by different ratio (Deng et al. 2018). So different mixed tree species and mixed ratio can lead to different stand preservation rates of mixed *Eucalyptus* plantation. In addition, the preservation rate of *N. cadamba* was the highest that 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 dominant tree species future. Therefore, the mixed pattern, the competitive ability and the interaction among tree species are the main factors, and such effects will determine the future succession tendency of the community.

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 is an important index of the structural stability of the stand, and also an important symbol to measure the quality of the stand and formulate the adjustment and optimization scheme when performing management (Yang 2012; Deng 2016). Yang et al. demonstrated that *Eucalyptus* with diameter class above 15 cm had a large proportion of more than 30% when *Eucalyptus* was mixed with *A. crassicarpa* by individuals (1 individual of *Eucalyptus* and 1 individual of *A. crassicarpa*) and by rows (1 row of *Eucalyptus* and 1 row of *A. crassicarpa*) (Yang et al. 2009). The study of Zhao showed that whether *E.urophylla* × *E.grandis* or *Styrax tonkinensis* of mixed forest, the proportion of less than 10 cm diameter wood was less than their respective pure stands, and that of 12~18 cm diameter wood was more than before, and large diameter trees of diameter larger than 20 cm appeared (Zhao 2011). Yang showed that the proportion of trees whose DBH was less than the average DBH in mixed forest of *E.urophylla* × *E.grandis* and *Castanopsis fissa* was less than that in pure forest, which is quite beneficial to the cultivation of large diameter *Eucalyptus* (Yang 2012). The results of our study that the proportion of trees with a height class more than 7 m was E>EA> EN>EP and the proportion of trees with diameter class above 7 cm was EA>EN> E>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 disturbance, which is consistent with the assessment of stability (Table 4, Table 5, Fig. 5).

Stem form and status of stem affects stand quality

The shape of stem growth is generally called stem form. The excellent stem form can not only improve the growth of trees, but also improve the wood quality (Zhang 2011; Castle et al. 2018). So the structure of the stem form of stand can assess the overall stand resistance of stand and present stand quality effectively. The distribution structure on the degree of straight-fullness and brunching and stem slant clearly demonstrated that most of the tree species presented a single stem, vertical growth, no slant of the stem form no matter that it was a mixed forest or a pure forest. But 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 contrasted to other two broad-leaf species. The mixed forest of *Eucalyptus* and *A. mangium* got a higher ratio of slant stems, and the mixed forest of *Eucalyptus* and *N. cadamba* got a higher ratio of tree branching stems. It is evident that some mechanisms of interaction existed in tree individuals. Generally, the tree individuals more or less 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. Such allelopathic mechanism of interaction and growth mechanism adapting to the environment are still worth further study.

Limitation

The row spacing was treated differently when planting these experimental forests in view of the differences of 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 taken into account as an important indicator when assessed the stand quality and stability. But 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 also worth to be further studied.

Conclusions

Assessing the stand stability of pure and mixed eucalyptus forests in typhoon-prone area is critical for choosing appropriate mixed pattern 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 in a lower level than that of pure *Eucalyptus* plantation and the height of EP appeared to be two-peak distribution. The stem of EN was testified to be more curving and brunching than that of pure *Eucalyptus* plantation, the stem of EA was testified to be more curving and slant than that of pure *Eucalyptus* plantation, and the stem of EP was testified to grew straightly. Only *A. mangium* can advance the stand stability of *Eucalyptus* plantation markedly, *P. elliottii* × *P. caribaea* can improve the stand stability of *Eucalyptus* plantation mildly and *N. cadamba* is not conducive to the stand stability of *Eucalyptus* plantation. To sum up, *A. mangium* is a more superior tree specie to mix with *Eucalyptus* for a more stable stand structure in windy areas so as 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.

Supplementary Information

Abbreviations

H: Height ; DBH: Diameter at breast height; N: *Neolamarckia cadamba*; A: *Acacia mangium* ;P: *Pinus elliottii* × *P. caribaea*; EN: Mixed forest of *Eucalyptus* and *N. cadamba*; EA: Mixed forest of *Eucalyptus* and *A. mangium*; EP: Mixed forest of *Eucalyptus* and *P. elliottii* × *P. caribaea*; E: Pure *Eucalyptus* forest.

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Authors' contributions

X.M. conceived and designed the study, provided suggestion of the manuscript. H.D. wrote and edited this manuscript. L.S. and J.Y. performed the data processing. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

References

Burdon JJ, Chilvers GA (1977) Preliminary studies on a native Australian eucalypt forest invaded by exotic pines. Oecologia 31(1):1-12.

Castle M, Weiskittel A, Wagner R, Ducey M, Frank J, Pelletier G (2018) Evaluating the influence of stem form and damage on individual-tree diameter increment and survival in the Acadian Region: Implications for predicting future value of northern commercial hardwood stands. Can J Forest Res 48(9):1007-1019.

Chen LY (2016) The afforestation effect of *Eucalyptus wetarensis* × *E.camaldulensis* mixed with *Pinus massoniana* or *Cunninghamia lanceolata*. Eucalypt Science & Technology 33(2):15-18.

Chu JZ, Luo JY, Yang NZ (1981) Experimental study on mixed afforestation of *Eucalyptus citriodora* and *Acacia*. Dynamics of Eucalyptus Science and Technology Tooperation (3):7-13.

Deng Q (2016) The visual simulation technology of stand structure analysis and adjustment.. Dissertation, Central South University of Forestry & Technology.

Deng ZY, Guo DQ, Huang PY, Zhang TS, Zhang F, Chen JB (2018) Initial growth effect of mixed forests with *Eucalyptus dunnii* and *Cunninghamia lanceolata*. Guangxi Forestry Science 47(3):329-331.

Diaz-Yanez O, Mola-Yudego B, Ramon Gonzalez-Olabarria J, Pukkala T (2017) How does forest composition and structure affect the stability against wind and snow? Forest Ecol Manag 401:215-222.

Gong GT, Li YQ, Zhu ZF, Chen JH, Mu CL, Wu XX, Zheng SW (2012) The suitable stand structure and hydrological effects of the cypress protection forests in the central Sichuan hilly region. Acta Ecologica Sinica 32(3):923-930.

Guo QQ, Zhang WH, Cao XP (2009) Establishment of an evaluation model of the forest community stability based on fuzzy synthetic evaluation: A case study of main forest communities in Huanglong Mountains. Sci Silva Sin 45(10):19-24.

Forrester DI, Bauhus J, Cowie AL (2006) Carbon allocation in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. Forest Ecol Manag 233(2-3):275-284.

Forrester DI, Bauhus J, Cowie AL, Mitchell PA, Brockwell J (2007) Productivity of three young mixed-species plantations containing N-2-fixing Acacia and non-N2-fixing Eucalyptus and Pinus trees in southeastern Australia. Forest Sci 53(3):426-434.

Forrester DI, Bauhus J, Khanna PK (2004) Growth dynamics in a mixed-species *Eucalyptus globulus* and *Acacia mearnsii*. Forest Ecol Manag 193(1-2):81-95.

Forrester DI, Theiveyanathan S, Collopy JJ, Marcar NE (2010) Enhanced water use efficiency in a mixed *Eucalyptus globulus* and *Acacia mearnsii* plantation. Forest Ecol Manag 259(9):1761-1770.

Gadow KV, Zhang CY, Wehenkel C, Pommerening A, Corral-Rivas J, Korol M, Myklush S, Hui GY, Kiviste A, Zhao XH (2012) Forest structure and diversity. In: Continuous Cover Forestry; Pukkala T, Gadow VK, (Eds). Springer Netherlands: Dordrecht, The Netherlands pp 29-83. https://doi.org/10.1007/978-94-007-2202-6_2

He KJ, Zheng HS, Lai HX, Huang SN, Cai MT (1988) Mixed experiment of eucalyptus fuelwood forest ⅰ. Preliminary report on mixed experiment of different density and different proportion. Forest research 1(6):671-676.

He LJ (2019) The study on growth rule and productivity of *Eucalyptus Castanopsis* Hystrix and *Castanopsis Fissa* mixed forest. Dissertation, Central South University of Forestry and Technology.

Huang XM, Liu SR, You YM, Wen YG, Wang H, Wang JX (2017) Microbial community and associated enzymes activity influence soil carbon chemical composition in *Eucalyptus urophylla* plantation with mixing N-2-fixing species in subtropical China. Plant Soil 414:199-212.

Huang XM (2013) The dynamic and regulation mechanisms of soil carbon in *Eucalyptus* plantations in south China. Dissertation, Chinese Academy of Forestry.

Hui GY (2013) Studies on the application of stand spatial structure parameters based on the relationship of neighborhood trees. Journal of Beijing Forestry University 35(04):1-9.

Hui GY, Zhang GQ, Zhao ZH, Hu YB, Liu WZ, Zhang SZ, Bai C (2016) A new rule of π value of natural mixed forest optimal stand state. Sci Silva Sin 52(5):1-8.

Jourdan M, Lebourgeois F, Morin X (2019) The effect of tree diversity on the resistance and recovery of forest stands in the French Alps may depend on species differences in hydraulic features. Forest Ecol Manag 450(117486):1-12.

Jiang J (2015) Study on structural dynamic and silvicultural system of conifer-broadleaved mixed plantation in southern tropical montane region. Dissertation, Chinese academy of forestry.

Kelty MJ (2006) The role of species mixtures in plantation forestry. Forest Ecol Manag 233(2-3):195-204

Kong L (2013) Optimal structure of three ecological forests in Jingouling forest. Dissertation, Beijing Forestry University.

Le Maire G, Nouvellon Y, Christina M, Ponzoni FJ, Gonçalves JLM, Bouillet JP, Laclau JP (2013) Tree and stand light use efficiencies over a full rotation of single- and mixed-species *Eucalyptus grandis* and *Acacia mangium* plantations. Forest Ecol Manag 288:31-42.

Li TT, Chen SZ, Wu SR, Wu KY, Lan Q (2016) Effect of the cutting intensity on structure characteristics of water conservation forest. Journal of Northwest Forestry University 31(05):102-108.

Liu CLC, Kuchma O, Krutovsky KV (2018) Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. Glob Ecol Conserv 15(e00419):1-13.

Ma JM; Li K (2004) Current situation of research and prospects on forest ecosystem stability. World Forestry Research 01):15-19.

Nouvellon Y, Laclau J, Epron D, Le Maire G, Bonnefond J, Goncalves JLM, Bouillet J (2012) Production and carbon allocation in monocultures and mixed-species plantations of *Eucalyptus grandis* and *Acacia mangium* in Brazil. Tree Physiol 32(6):680-695.

O'Connor CD, Falk DA, Lynch AM, Swetnam TW, Wilcox CP (2017) Disturbance and productivity interactions mediate stability of forest composition and structure. Ecol Appl 27(3):900-915.

Peng SL (1987) Measurement of stability and dynamics of forest community — Analysis of age structure. Guangxi Plants 7(1):67-72.

Pereira APA, Durrer A, Gumiere T, Goncalves JLM, Robin A, Bouillet J, Wang J, Verma JP, Singh BK, Cardoso EJBN (2019) Mixed *Eucalyptus* plantations induce changes in microbial communities and increase biological functions in the soil and litter layers. Forest Ecol Manag 433:332-342.

Santos FM, Balieiro FDC, Ataíde DHDS, Diniz AR, Chaer GM (2016) Dynamics of aboveground biomass accumulation in monospecific and mixed-species plantations of *Eucalyptus* and *Acacia* on a Brazilian sandy soil. Forest Ecol Manag 363:86-97.

Santos FM, Chaer GM, Diniz AR, Balieiro FDC (2017) Nutrient cycling over five years of mixed-species plantations of *Eucalyptus* and *Acacia* on a sandy tropical soil. Forest Ecol Manag 384:110-121.

Spulák O, Souček J, černý J (2018) Do stand structure and admixture of tree species affect Scots pine aboveground biomass production and stability on its natural site? Journal of Forest Science (Prague) 64(11):486-495.

Voigtlaender M, Brandani CB, Caldeira DRM, Tardy F, Bouillet JP, Goncalves JLM, Moreira MZ, Leite FP, Brunet D, Paula RR, Laclau JP (2019) Nitrogen cycling in monospecific and mixed-species plantations of *Acacia mangium* and *Eucalyptus* at 4 sites in Brazil. Forest Ecol Manag 436:56-67.

Wan P, Liu WZ, Liu RH, Wang P, Wang HX, Hui GY (2020) Effects of structure-based forest management on stand space structure and its stability of mixed oak-pine forest. Sci Silva Sin 56(4):35-45.

Wei HY; Dong LB; Liu ZG (2019) Spatial structure optimization simulation of main forest types in Great Xing’an Mountains, Northeast China. Chinese Journal of Applied Ecology 30(11):3824-3832.

Wen GY, Zhang ZF, Zhou XG, Zhu HG, Wang L, Cai DX, Jia HY, Ming AG, Lu LH (2020) Effects of precious and rare native tree species mixed with *Eucalyptus* on ecosystem biomass and carbon storage. Guangxi Sci 27(2):111-119.

Wen YG, Liu SR, Chen F (2005) Effects of continuous cropping on understorey species diversity in Eucalypt plantations. Chinese Journal of Applied Ecology 16(9):1667-1671.

Xing CW, Huang XR, Li YL, Ma ZW, Fu XY (2013) Ecological stability of sand-fixed plantations in Huangyangtan. Sci Silva Sin 50(5):101-107.

Yang ZJ, Xu DP, Chen WP, Huang LJ, Li SJ, Chen Y (2009) Growth effect of *Eucalyptus acacia* mixed plantation in South China.. Chinese Journal of Applied Ecology 20(10):2339-2344.

Yang R, Zhao PX, Li WZ, Wang BH, Zhou YB (2020) Research on relationship between stability and spatial structure of Chinese pine plantation based on rule of π value. Journal of Central South University of Forestry & Technology 40(5):95-103.

Yang WH (2012) Effect of mixed afforestation of *Eucalyptus* and *Castanopsis fissa*. Guide of Sci-Tech Magazine (20):10-11.

Yao XY, Li YF, Liao LN, Sun G, Wang HX, Ye SM (2019) Enhancement of nutrient absorption and interspecific nitrogen transfer in a *Eucalyptus urophylla* × *E. grandis* and *Dalbergia odorifera* mixed plantation. Forest Ecol Manag 449(117465).

Ye SM, Wen YG, Yang M, Liang HW, Lan JX (2010) Correlation analysis on productivity and plant diversity of *Eucalyptus* plantations under successive rotation. Acta Botanica Boreali-Occidentalia Sinica

30(7):1458-1467.

Yu XW, Song XS, Kang FF, Han HR (2015) Stability evaluation of typical forest communities in the source of Liaohe River in northern Hebei Province. Journal of Arid Land Resources and Environment 29(05):93-98.

Yücesan Z, özçelik S, Oktan E (2015) Effects of thinning on stand structure and tree stability in an afforested oriental beech (Fagus orientalis Lipsky) stand in northeast Turkey. J Forestry Res 26(1):123-129.

Zhou XG, Zhu HG, Wen YG, Goodale UM, Zhu YL, Yu SF, Li CT, Li XQ (2020) Intensive management and declines in soil nutrients lead to serious exotic plant invasion in *Eucalyptus* plantations under successive short-rotation regimes. Land Degrad Dev 31(3):297-310.

Zhang P, Pang SJ, Yang BG, Liu SL, Jia HY, Chen JB, Guo DQ (2021) Effects of different mixed models on stand growth, litter yield and soil nutrients of *Eucalyptus* Plantation. Journal of Northwest A & F University (Natural Science Edition) 49(2):1-7.

Zhang Q (2011) Study on the effect of green-pruning on improve the wood quality of Chinese fir. Dissertation, Chinese academy of forestry.

Zhang ZF (2020) Effects of mixing precious indigenous tree species and *Eucalyptus* on biomass, Carbon Stocks And Soil Physicochemical Preperties. Dissertation, Guangxi University.

Zhao HZ (2011) Analysis on effect of mixed planting of *Eucalyptus* PPS and *Styrax tonkinensis* (Pierre) Craib. Modern Agricultural Sciences and Technology 12):195-196.

Zheng HS, He KJ (1992) Experiment on different mixed ways of *Eucalyptus* 'Leilin No.1' and *Acacia auriculiformis*. Forest Science and Technology (10):21-24.

Zhu LY, Wang XH, Chen FF, Li CH, Wu LC (2019) Effects of the successive planting of *Eucalyptus urophylla* on soil bacterial and fungal community structure, diversity, microbial biomass, and enzyme activity. Land Degrad Dev 30(6):636-646.

Zhu YJ (2016) The spatial structure-control technology of eucalyptus plantation based on the forest form improvement. Dissertation, South China Agricultural University.

Figures

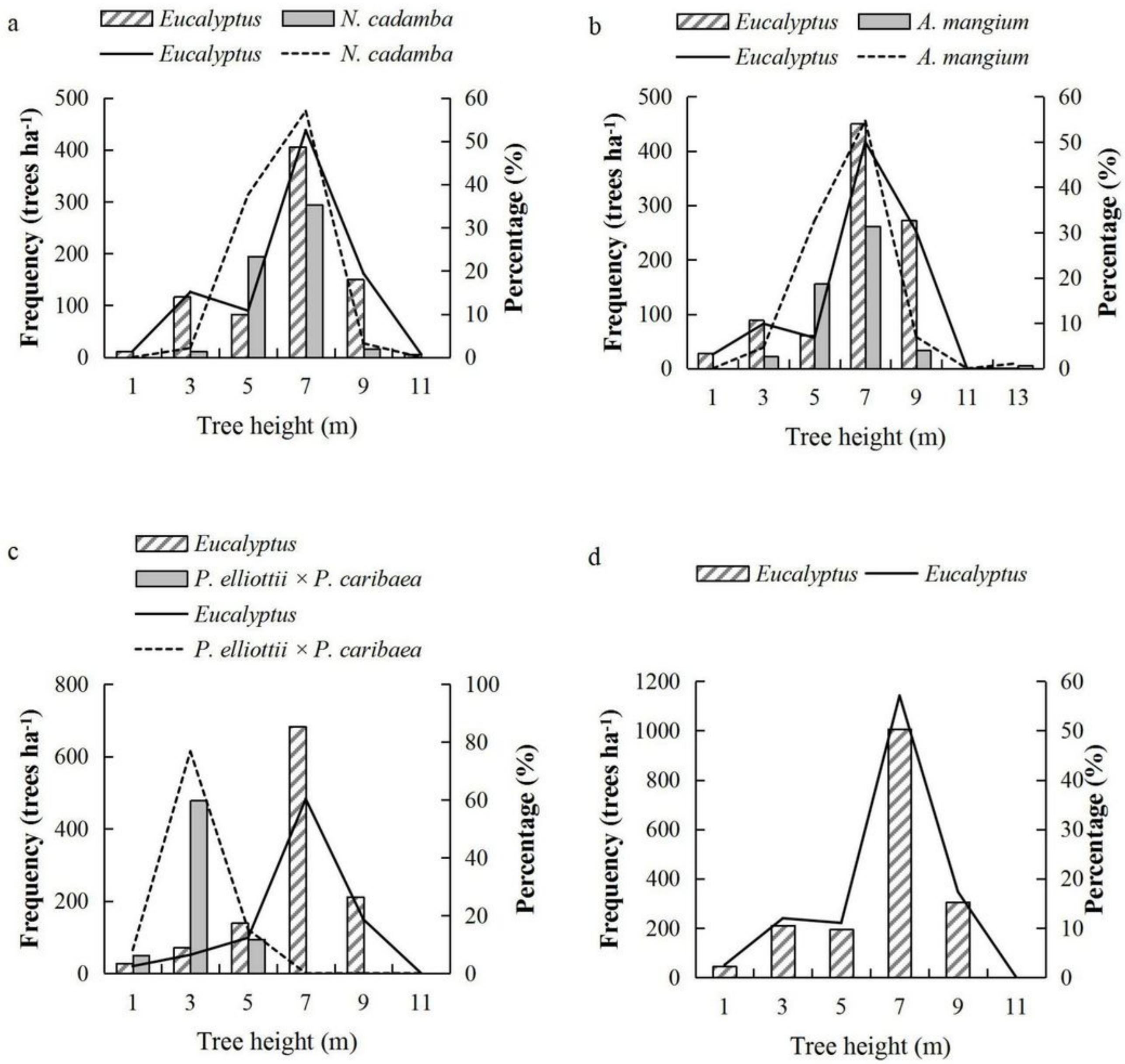

Figure 1

Tree height distribution of E. urophylla × E. grandis at the age of 18 months and of mixed tree specie at the age of 38 months in monocultures and mixtures. Height of the histograms show the distribution frequency of tree height of each tree species per hectare. The line show 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 (E).

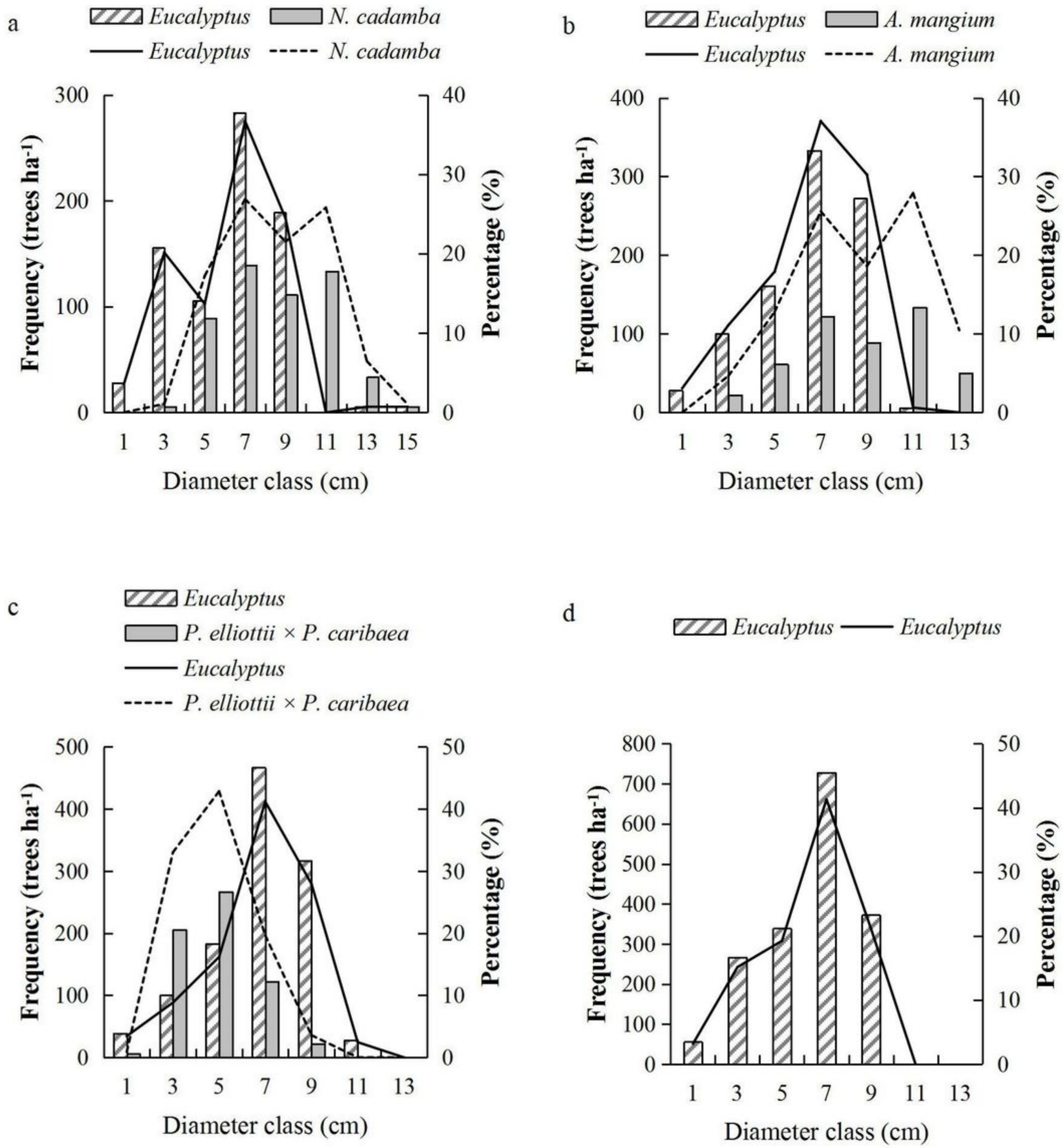

Figure 2

Diameter distribution of E. urophylla × E. grandis at the age of 18 months and of mixed tree specie at the age of 38 months in monocultures and mixtures. Height of the histograms show the distribution frequency of diameter of each tree species per hectare. The line show 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 plantationof Eucalyptus and P. elliottii × P. caribaea (EP); d: Pure forest of E. urophylla × E. grandis (E).

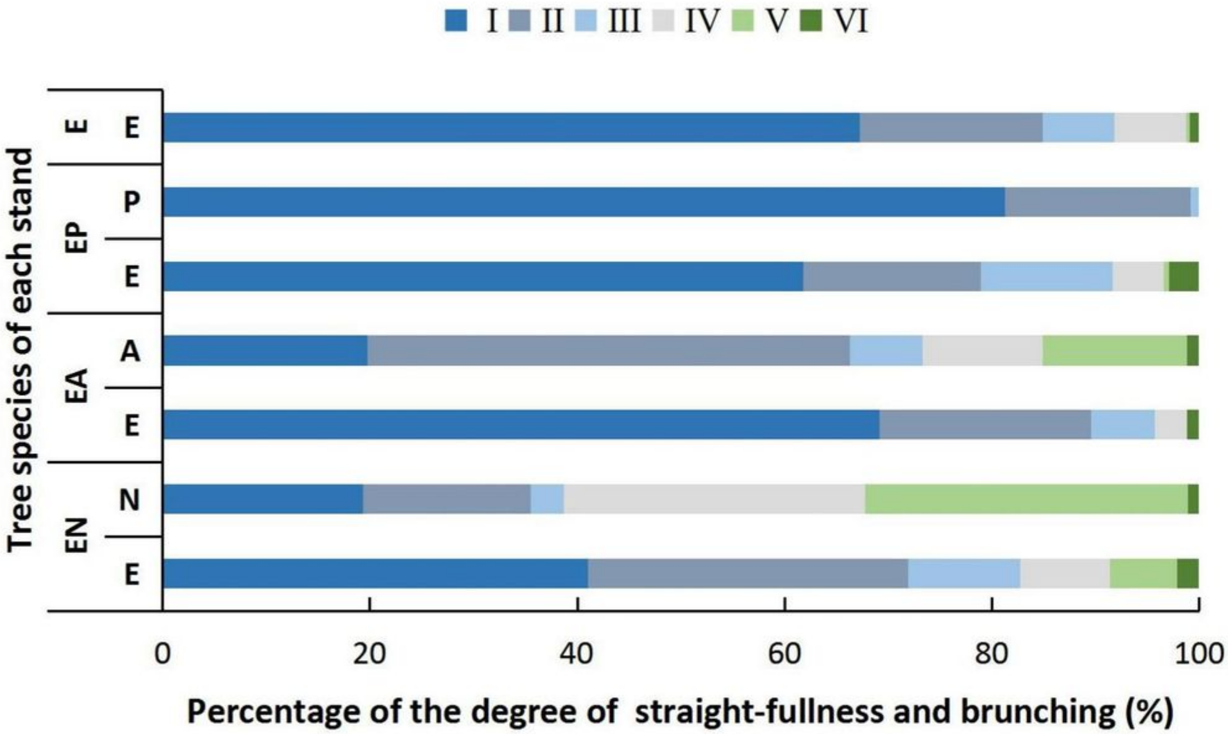

Figure 3

Degree of straight-fullness and brunching of tree stems of different tree species in each stand. Length of different colors show 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); E: Pure forest of E. urophylla × E. grandis (E).

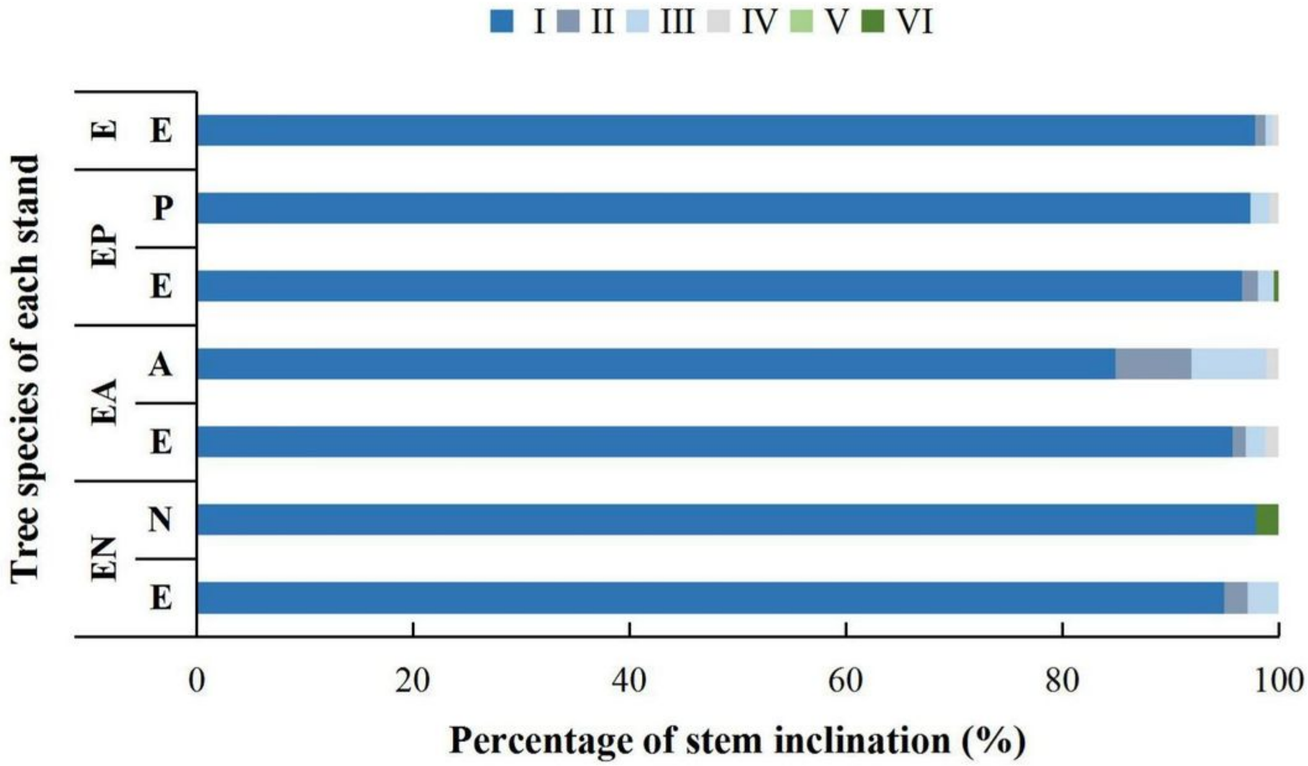

Figure 4

Degree of stem slant of different tree species among pure and mixed forests of Eucalyptus. Length of different colors show the percentage of different grades of stem slant. 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); E: Pure forest of E. urophylla × E. grandis (E).

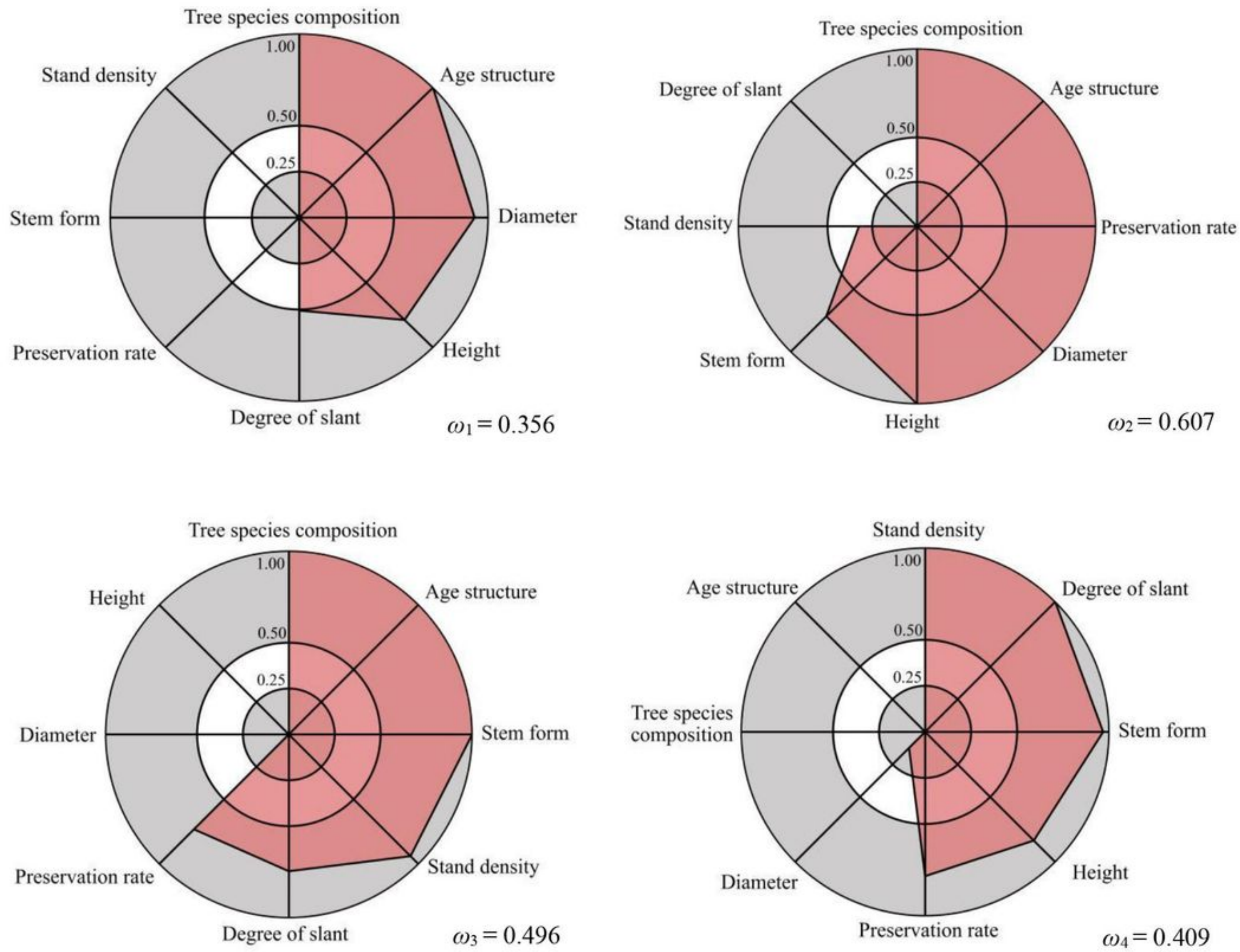

Figure 5

Stand state unit circles of pure and mixed Eucalyptus forests of different tree species. ω1 is the stable status value of mixed plantation of Eucalyptus and N. cadamba (EN); ω2 is the stable status value of mixed plantation of Eucalyptus and A. mangium (EA); ω3 is the stable status value of mixed plantation of Eucalyptus and P. elliottii × P. caribaea (EP); ω4 is the stable status value of pure forest of E. urophylla × E. grandis (E).