Key traits influencing wind resistance of Eucalyptus camaldulensis

Shang Xiu-hua
Research Institute of Fast-growing Trees, CAF
Zhang Pei-jian
Research Institute of Fast-growing Trees, CAF
Liu Guo
Research Institute of Fast-growing Trees, CAF
Wu Zhi-hua (wzhua2889@163.com)
Research Institute of Fast-growing Trees, CAF

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Abstract

Background

Wind is an important driving factor influencing forest structure, ecology, and the carbon cycle in temperate and tropical regions. Damage from typhoons poses a significant threat to eucalyptus production in coastal regions of southeast China. However, few strategies have been used and account for key traits impact on wind damage/resistance of eucalyptus. To identify key factors affecting eucalyptus wind resistance, 20 *Eucalyptus camaldulensis* genotypes were selected, and wind damage indices and traits were measured and evaluated using correlation analysis and principal component analysis.

Results

We identified a correlation between tree traits, wind damage indices, and the traits related to H, V, FP BT, FL, and FW. Five PCs from the above-mentioned traits were obtained and could represent the standing tree traits explained by PCA. PCs and tree-pulling variables were further used for typical correlation and path analyses. Canonical correlation analysis showed the top two canonical correlation coefficients were 0.9547 and 0.9012, respectively, while PC2 reflected that the growth traits were the main trait affecting pull tree variables. The PA-OV model and its modifications with PC functions and tree-pulling variables were introduced and developed for wind resistance estimation. The fitting effect of the two models and the observed data was good, with a P-value of 1.000, RMSEA of 0.000, and other goodness of fit indices over 0.9. Based on effects from model 2, PC4 had the greatest impact on tree-pulling variables. Therefore, our results implied that PC4, composed of holocellulose content, lignin, and fibre width, was the most important factor affecting standing tree stability under windy conditions.

Conclusion

This study provides insights into forest management and planning in coastal typhoon prone areas. Determining the effect of wind on trees can expand our understanding of the factors that contribute to wind damage, thereby improving management practices.

1. Background

Wind, a natural disturbance that forests are vulnerable to, is one of the most powerful environmental factors [1]. Wind can uproot, crack, split, or break tree trunks, branches, and limbs and cause serious damage to trees. Trees in many parts of the world die from wind damage every year, resulting in huge economic and habitat losses [2–4]. In the context of climate change, wind damage of trees and forests may become more frequent due to the intensity of low- pressure systems outside the tropics or in the tropics (hurricanes or typhoons) are increasing [5, 6]. Wind throw and snap are the most common and serious wind disasters, which not only threaten forest productivity but are also a potential factor limiting tree height and forest carbon storage [7–9]. Therefore, it is necessary to understand the wind damage process and its impact on trees to reduce the impact of wind damage on trees and forest management.

The influence of wind on trees and stands mainly depends on wind power and tree stability [10]. If the wind loading exceeds the resistance of the trunk or root/soil system, the trees will break or be uprooted. Many factors affect tree wind damage, including climate, topography, soil, standing wood characteristics, and forest management intervention [1, 11, 12]. Peltola et al. [13] and Zubizarreta-Gerendiain et al. [14] found that stand and site characteristics influenced stand wind resistance. The wind resistance of trees or stands also varies with stand age [15, 16]. Nolet et al. [17] found that tree species and tree trunk size are important for wind damage resistance. Tree diameter and species type significantly impact the risk of trunk breakage or uprooting in severe storms [18]. The soil physical properties determine the root morphology, overall size, and soil-root block (root ball) shape, which is the most important determinant of anchoring forest roots, and the interaction between roots and soil significantly affects tree trunk responses to wind [19, 20]. As a complex tree structure system, Spatz et al. [21] believed that the swing state of tree crowns under wind loading has a greater impact on tree trunks than wind speed and wind direction. Gardiner et al. [22] believed that the wood density and physical-mechanical properties of trunks influence the response of trees to wind loading. Trees with a high wood base density and low microfilament angle show greater wind resistance [23, 24]. A high basic density of wood would make wood materials higher per unit volume and confer stronger crushing resistance [25]. However, Read et al. [26] found that reducing wood density does not necessarily reduce wind resistance. Wind resistance is also affected by other characteristics, including cell-level characteristics (such as MFA) and the entire plant structure. Wind and trees have a complex interaction, which is influenced by several factors. Virot et al. [27] argued that a wind speed of approximately 42 m/s can break over 50% of all trees in the forest, regardless of tree characteristics. Albrecht et al. [28] suggested that significant biomechanical ingredients are absent in the Virot et al. [27] wind speed model at which trees break. Therefore, the key traits/factors influencing the wind resistance of trees for forestry production and management remain to be identified.

Eucalyptus is an important plantation cultivation and management tree species in southern China due to its fast growth, high yield, short rotation, and high economic benefit [29–32]. However, tropical cyclones in the western North Pacific affect the southern coastal areas of China. Typhoons (strong storms formed in the Pacific) are frequent in the summer and greatly impact forestry in China's coastal areas [33, 34]. It is important for widely planted eucalyptus plantations to assess their vulnerability to climate change [35]. In particular, the destruction of typhoons can restrict the production of eucalyptus wood [36, 37]. In recent years, few studies have investigated the wind resistance mechanism of eucalyptus. *Eucalyptus camaldulensis* is an evergreen tree with drought, barren, salt, and frost resistance [38], which are important genetic traits for eucalyptus breeding in China [39, 40]. The main damage caused by typhoons to trees is tree uprooting and stem/branch breaking [41, 42]. In this study, to determine key traits affecting eucalyptus wind resistance of stem/branch breakage, 20 families and genotypes of *E. camaldulensis* were investigated, and their traits linked to the ability of trees to resist wind damage were evaluated using a new method focusing on the wind damage. This study explains the factors that contribute to wind damage to eucalyptus trees, and the findings provide insights for reducing the risks associated with commercial forest management in coastal areas.

2. Results And Analysis

2.1. Analysis of standing tree traits

Tables 1 and Appendix C list the basic information of the different traits of the 20 *E. camaldulensis* families; growth traits: tree height (H) varied from 2.0 m to 17.9 m, with an average value of 10.52 cm and its CV of 30%. The average DBH of the families was 10.45 cm, the average individual volume per tree was 51.40 dm^3, and the CV was 59%. The average BT was 6.02 mm, and its CV was the smallest among the growth traits. Although some coefficients of variation were relatively large, there were no significant differences in growth traits among the different families.

Table 1
Basic Descriptive statistics and analysis of variance (ANOVA) among families.

Traits	Minimum	Maximum	Means	Std.dev.	CV/%	Skewness	Kurtosis	F-Ratio	P-value
H/m	2.0	17.9	10.52	3.16	30.1	-0.60	-0.05	1.157	0.300
DBH/cm	3.3	17.3	10.45	2.80	26.8	-0.29	-0.20	1.213	0.252
VOL/dm^3	3.71	165.60	51.40	30.33	59.0	0.69	0.51	1.080	0.376
BT/mm	0.00	16.20	6.02	1.89	31.4	0.89	4.14	1.272	0.207
WDB/g/cm^3	0.171	0.653	0.442	0.043	9.7	-0.16	11.44	1.793	0.027
PN	8.0	17.8	13.21	1.67	12.64	0.16	7.32	1.238	0.232
FP/μs	390	615	497.51	47.46	9.5	0.30	-0.56	6.471	0.000
FL/mm	0.49	0.70	0.58	0.04	6.6	0.24	0.38	3.309	0.000
FW/μm	21.3	30.1	25.29	1.27	5.0	-0.04	0.76	2.957	0.000
FLW	19.8	27.9	22.92	1.48	6.5	0.44	0.20	1.362	0.152
LC/%	19.37	26.89	22.95	2.02	8.8	-0.24	-0.67	50.215	0.000
HC/%	76.91	82.84	79.83	1.70	2.1	0.25	-1.13	137.768	0.000
CC/%	42.26	55.13	47.97	3.25	6.8	0.15	-0.72	143.063	0.000
MOR/MPa	26.8	103.1	76.4	12.7	16.7	-0.50	0.53	10.180	0.000
MOE/MPa	3987.0	10498.0	7132.0	1350.0	18.9	-0.21	-0.26	6.094	0.000
SSG/MPa	11.3	39.3	25.1	5.1	20.2	-0.11	0.23	14.472	0.000
CP/MPa	32.5	59.3	46.4	5.6	12.1	-0.23	-0.48	18.209	0.000
WD1/ score	1.0	5.0	1.50	0.80	53.5	2.43	7.51	1.858	0.018
WD2 /score	0.0	5.0	0.61	0.78	128.1	2.46	10.68	1.456	0.102
WD3/ score	0.0	5.0	0.68	1.12	165.6	2.09	4.19	1.588	0.059
WD4/ score	1.0	5.0	1.65	1.35	81.6	1.88	1.87	2.238	0.003
WD5/ score	1.3	2.5	1.87	0.37	20.0	0.20	-1.35	1.728	0.036

Wood density and non-destructive testing properties of wood: the maximum WBD reached 0.653 g/cm^3, the average value was 0.442 g/cm^3, and the CV was 9.7%. The average PN value was 13.2, and its CV was 12.64%. The average FP of standing trees was 497.51 μs. The kurtosis coefficient of WBD (11.4) was greater than three, and the box plot in Appendix C showed that the WBD data were concentrated, while the CV of FP was 9.5%, but there were significant differences in WBD and FP among different families.

Fibre morphology and content: FL was between 0.49–0.70. The average FL was 0.58 mm, and its CV was only 6.6%. However, the FW means was 25.29 μm in the range of 21.3–30.1 μm with 5.0% CV. Therefore, the CV of FLW was also small (6.5%). Nevertheless, there were significant differences in FL and FW among different families. Further analysis results showed that LC varied from 19.37–26.89%, the average content of LC was 22.95%, the minimum of HC was 76.91%, the maximum value was 82.84%, and the average HC was 79.83%. The CC was 42.26–55.13%, with an average of 47.97%. Similarly, the LC, HC, and CC contents in different families were significantly different.

Physical and mechanical properties of wood: the results showed that MOR ranged from 26.8 to 103.1 MPa with an average of 76.4 MPa, and CV of MOR was 16.7%. MOE ranged from 3,987.0 to 10,498.0 MPa with an average of 7,132.0 MPa, and its CV was 18.9%. The minimum value of SSG was 11.3 MPa, the maximum SSG was 39.3 MPa, and the average value was 25.1 MPa. CP minimum value was 32.5 MPa, CP maximum value was 59.3 MPa, the average value was 46.4 MPa, and the CV was 12.1%. There were obvious differences among the different *E. camaldulensis* families.

Wind damage indices of standing trees: due to different typhoons with different strengths, the wind damage of eucalyptus stands at different ages was different. As shown in Table 1, WD1 and WD3 scores of different families were mainly 1 and 2, respectively. The average scores of WD1, WD2, and WD3 were 1.50, 0.61, and 0.68, respectively. The average WD5 was 1.87. In general, there were significant differences in WD among families, especially in WD4 and WD5, and the wind damage scores of CA21, CA22, CA26, and CA27 from Australia (CA seedlot) were significantly lower than those from India (C0 seedlot).

2.2 Correlation analysis of each trait

It can be seen from the correlation matrix in Fig. 1 that the clustering was based on the correlation degree of different traits: the wind damage indices of WD1-WD2 and WD3-WD5 were in one class; growth traits such as H, DBH, VOL, and BT were in one class; non-destructive testing properties of FP and PN were in one class; physical and mechanical properties of MOE, SSR, and CP were in one class; fibre morphology and content of LC, HC, CC, FL, and other wood properties, including FW and FLW, were in one class. Strong correlation within the same category. For example, the correlation coefficient between wood properties was more than 0.6 and with a significant correlation at the 0.01 level. Similarly, the non-destructive testing properties of wood and wood fibre properties were the same. The wind damage indices had a very high correlation with growth traits (H, VOL, and PN) and FL.

2.3 Principal Component Analysis of traits

According to the PCA of 17 traits other than wind damage index, it can be seen from Table 2that the contribution rates of the five principal components (PCs) were 33.457%, 16.088%, 12.446%, 10.812%, and 7.427%, respectively, and the cumulative contribution rate was 80.230%. The five PCs represented over 80% of the total variation, therefore, the original 17 traits were transformed into five new independent comprehensive indices or five PCs. PC1 had a strong positive correlation with MOE, MOR, WBD, CP, and SSG, with an eigenvalue of 5.688, which mainly reflected the physical and mechanical properties of standing wood. PC2 had the largest positive correlation with DBH and BT, with an eigenvalue of 2.735, which mainly reflected the growth status of standing wood. PC3 had the largest positive correlation with DBH and BT. There was a strong correlation between CC and FL, with an eigenvalue of 2.116, and mainly reflected the chemical composition of the fibre and its morphological index of standing wood. PC4 was positively correlated with HC, FW, and LC, which were mainly wood fibre traits. PC5 was closely correlated with FLW and LC, which are also related to wood fibres. PC3, PC4, and PC5 mainly belonged to the chemical composition and fibre morphology traits of standing wood.

Table 2
Eigenvectors and percentages of the accumulated contribution of principal components (PCs).

Traits	Principal component				
	1	2	3	4	5
H	-0.297	0.590	0.038	-0.217	-0.330
DBH	-0.249	0.763	-0.136	0.317	0.313
VOL	-0.287	0.869	-0.023	0.207	-0.022
BT	-0.504	0.710	0.068	0.140	0.221
MOR	0.876	0.253	0.064	-0.194	0.182
MOE	0.892	0.056	0.113	-0.124	0.099
SSG	0.735	0.279	0.253	-0.241	-0.099
CP	0.750	0.271	0.344	-0.260	0.102
WBD	0.822	0.285	0.193	-0.208	0.122
LC	-0.058	0.104	-0.446	-0.532	0.536
HC	0.513	0.111	0.417	0.638	-0.038
CC	0.006	-0.094	0.812	0.291	-0.095
FL	0.576	0.177	-0.604	0.350	-0.309
FW	0.476	-0.098	-0.415	0.640	0.242
FLW	0.281	0.328	-0.376	-0.215	-0.681
FP	-0.759	0.243	0.358	-0.230	-0.094
PN	-0.615	-0.073	0.125	0.022	0.053
Eigenvalue EV	5.688	2.735	2.116	1.838	1.263
Contribution rate (%) CR	33.457	16.088	12.446	10.812	7.427
Cumulative contribution rate (%) CCR	33.457	49.545	61.991	72.803	80.230

2.4 Tree-pulling test of standing trees

The wind damage data of 20 standing trees were simulated and obtained using a tree-pulling test. The pulling forces of the *E. camaldulensis* C033 family tree were observed when the standing tree was pulled and released in the whole tree pulling test (Appendix D). Since the tested trunk was a bioelastic body and wind disturbance to the crown occurred, the tree had a certain vibration, leading to a small range of variation in the pulling force. In general, with the increase in pulling force, the pulling force was linearly related to the elastic deformation X1 and inclination angles X2 and X3 of the trunk. The variables were obtained via a tree-pulling test, and their fitted models were performed using DataFit software (version 9.0 [43]); the results are shown in Table 3. A significant correlation was observed between the pulling force (Y) of the standing tree and the trunk deformation degree (X1), the inclination angle between the standing tree and the vertical direction of the tensile direction (X2), and the inclination angle of the standing tree in the tensile direction (X3). Therefore, the fitting regression equation ($y = aX1 + bX2 + cX3 + d$) can be established between Y_{force} and X1, X2, and X3. The R^2 of *E. camaldulensis* regression equations ranged from 0.6371 to 0.9673, and all fitting equations reached an extremely significant level ($P < 0.01$). These results showed that the equations could accurately reflect the dynamic relationship between Y_{force} and X1, X2, and X3. The larger the fitting equation coefficient "a" was, the greater Y_{force} of standing trees would be under the same deformation degree. The larger the fitting equation coefficient “b” was, the greater the pulling Y_{force} is under the same vertical inclination angle of the standing stand and the pulling force direction. The larger the parameter “c” of the fitting equation, the greater the pulling force of the standing tree will be under the inclined angle of the same pulling force direction.

According to the different equations of the standing tree (Table 3), the deformation X1 and inclination angles X2 and X3 of the standing tree were obtained when Y_{force} was maximum in the tree-pulling test (Appendix E), due to the differences in tree shape, size, and physical properties, the Y_{force} maximum was also different, and the elastic deformation X1, inclination angle, and direction (X2 and X3) were different.

Table 3
Regression equations and regression statistics of pull tree and three factors in pull tree simulation wind damage tree test.

Family	Fitted equation	a	b	c	d	SEE	R^2	DF	SS	MS	F value
CA26	Y = aX1 + bX2 + cX3 + d	-0.0003	-0.1739	0.0492	-0.1720	0.1028	0.9050	3	847.75	282.58	26753.22
CA21	Y = aX1 + bX2 + cX3 + d	0.0000	0.1172	0.0433	0.0164	0.0744	0.8960	3	95.54	31.85	5744.26
CA22	Y = aX1 + bX2 + cX3 + d	-0.0004	-0.1496	0.0656	-0.0980	0.1066	0.8799	3	316.43	105.48	9283.49
CA28	Y = aX1 + bX2 + cX3 + d	-0.0000	0.1260	-0.0742	0.0027	0.1935	0.7937	3	624.47	208.16	5558.42
CO46	Y = aX1 + bX2 + cX3 + d	-0.0005	0.0038	-0.0342	0.2110	0.1221	0.6371	3	106.51	35.50	2380.32
C076	Y = aX1 + bX2 + cX3 + d	-0.0002	-0.2320	0.0976	-0.0517	0.1757	0.8977	3	1295.41	431.80	13990.91
C079	Y = aX1 + bX2 + cX3 + d	-0.0002	0.2355	0.0865	0.0013	0.1012	0.9600	3	1301.67	433.89	42330.83
C05	Y = aX1 + bX2 + cX3 + d	-0.0007	-0.2068	0.1115	0.0601	0.0736	0.8983	3	221.38	73.79	12659.10
CA27	Y = aX1 + bX2 + cX3 + d	-0.0003	0.0020	-0.0011	0.0115	0.1019	0.8431	3	184.66	61.55	5923.75
C013	Y = aX1 + bX2 + cX3 + d	-0.0003	-0.0114	0.0140	0.6598	0.3941	0.8472	3	610.34	203.45	1309.79
C033	Y = aX1 + bX2 + cX3 + d	-0.0011	0.3382	0.7866	-0.0618	0.1284	0.8396	3	405.45	135.15	8190.75
C04	Y = aX1 + bX2 + cX3 + d	-0.0006	-0.0075	-0.0128	-0.0142	0.1013	0.9110	3	262.88	87.63	8542.76
C036	Y = aX1 + bX2 + cX3 + d	-0.0003	0.0028	0.0588	-0.0133	0.1151	0.9120	3	731.80	243.94	18421.70
CA9	Y = aX1 + bX2 + cX3 + d	-0.0010	0.4044	-0.0487	0.1034	0.1390	0.9673	3	1618.50	539.50	27926.84
CA16	Y = aX1 + bX2 + cX3 + d	0.00005	-0.0241	0.1146	-0.0058	0.1780	0.7077	3	259.10	86.67	2727.01
C023	Y = aX1 + bX2 + cX3 + d	-0.0002	-0.2123	0.0994	0.0188	0.0982	0.9737	3	3309.73	1103.24	114199.56
CA8	Y = aX1 + bX2 + cX3 + d	-0.0003	-0.04238	0.0564	0.0264	0.1347	0.9158	3	2668.23	889.41	49009.53

Family	Fitted equation	a	b	c	d	SEE	R^2	DF	SS	MS	F value
CA7	Y = aX1 + bX2 + cX3 + d	0.0016	-0.0546	0.03386	-0.0204	0.0852	0.9322	3	112.88	37.63	5187.85
C014	Y = aX1 + bX2 + cX3 + d	-0.0005	0.0999	0.0053	-0.0013	0.0670	0.9325	3	434.90	144.97	32238.10
CO80	Y = aX1 + bX2 + cX3 + d	-0.0019	0.1972	-0.0247	0.0038	0.0876	0.8848	3	338.73	112.91	14699.96

2.5 CCA

Due to the obvious differences among *E. camaldulensis* families of different forest ages and the apparent differences in typhoon loading on standing trees, the correlation between different characters and wind damage indices in several typhoon hits was not strong (Fig. 1).The correlation analysis between single-factor variables cannot provide the real cause of forest wind resistance. CCA was performed between the five PC1-PC5 obtained from the PCA of wind resistance-related traits and the four variables, Y_{force}, X1, X2, and X3, from wind damage simulated by the tree-pulling test, to obtain the key traits affecting tree wind resistance.

As shown in Table 4, the first two canonical correlation coefficients were 0.9547 and 0.9012, respectively, which were highly correlated at extremely significant levels in the statistical test ($P < 0.01$). The first two pairs of canonical covariates were used to analyse the relationship between standing tree traits and variables in the tree-pulling test (Table 5). For eucalyptus trait variables, the first covariate U1 in the set1 data was highly affected by PC2 (-0.7820), and the second covariate U2 was strongly affected by PC4 (-0.6311). For tree-pulling variables, the first covariate V1 consisted of X2 (0.5432), X3 (-0.5354), X1 (0.3086), and Y_{force} (-0.2399), while the second covariate V2 was highly correlated with X3 (0.6384), X1 (0.6213), X2 (0.5819), and Y_{force}(0.5348).

Table 4
Statistical analysis of canonical correlation.

Dimension	Correlation coefficient	Wilk's	F	Chi-square value	Df	P value
1	0.9547	0.0116	5.3046	37.4328	20	5.7641×10^{-6}
2	0.9012	0.1310	3.0857	32.0405	12	5.3751×10^{-3}
3	0.5446	0.6979	0.8536	26.0000	6	0.5411
4	0.0883	0.9922	0.0550	14.0000	2	0.9467

Table 5
PCs of eucalyptus traits and coefficient of variables in canonical correlation analysis of pull tree test factor.

Set1	PCA1	PCA2	PCA3	PCA4	PCA5
U1	0.1745	-0.7820	0.1571	0.4747	-0.3053
U2	-0.4526	-0.5936	0.0290	-0.6311	0.2806
U3	-0.1410	0.1589	0.4683	-0.3105	-0.7867
U4	0.8602	-0.1008	-0.0641	-0.5312	-0.0283
Set2	X1	X2	X3	Yforce	
V1	0.3086	0.5432	-0.5354	-0.2399	
V2	0.6213	0.5819	0.6384	0.5348	
V3	1.1045	-0.6617	-0.2802	0.4875	
V4	0.4110	0.0038	-0.5879	1.1334	

2.6 Estimated Path analysis model

The five PC1-PC5 and the four variables of Y_{force}, X1, X2, and X3 were obtained when the maximum Y_{force} in the tree-pulling test was used for path analysis using the traditional PA-OV model (Fig. 2). In the model, the PC variables (PC1-PC5) were obtained by PCA, which was uncorrelated and related to the residuals of the tree-pulling variables (X1, X2, X3, and Y_{force}).

The correlation coefficients of the two variable residuals from the four tree-pulling variables are shown in Fig. 2. The maximum value (absolute value) of the correlation coefficients was − 0.457 from X1 and Y_{force}, which indicated that the two variables were related but not significant ($P = 0.070$). The remaining of model 2 (Fig. 3) showed that the influence effect (absolute value) of PC1-PC5 on X1 ranked from high to low was PC4 > PC2 > PC1 > PC3 = PC5, and its effect on X2 was PC4 > PC1 > PC2 > PC5 > PC3; PC4 had the strongest effect on Y_{force} with − 0.907 coefficient, and other variables showed no significant difference; among them, the path of PC4 → X1 ($P = 0.048$), PC4 → X2 ($P = 0.002$), PC1 → X2 ($P = 0.013$), and PC2 →X3 ($P < 0.001$) reached significant levels. PC4 was an important factor for the stability of standing trees, followed by PC1.

Considering the causal relationship between the model variables, the path diagram of model 2 was modified from that of model 1(Fig. 2). In Fig. 2, the values close to the four tree-pulling variables were the square value of the multiple correlation coefficient (R^2), which was the explanatory variation of predictive variables to standard variables. The five PCs could explain 30.2% of X1, 51.1% of X2, 74.3% of X3, and 29.5% of Y_{force}. Figure 3 and Table 6 suggest that model 2 could significantly improve the explained variance of X1 and Y_{force}; their R^2 increased from 0.302 (model 1) to 0.410 (model 2), and from 0.295 (model 1) to 0.614 (model 2), respectively. Therefore, the regression weight calculation of estimated model 2 based on the maximum likelihood method is described below.

The direct effects from model 2 on each tree-pulling variable were as follows:

$X1 = -0.242*PC1 -0.280*PC2 + 0.161*PC3 -0.617*PC4 + 0.161*PC5 -0.468*X2 -0.073*X3$ (1)

$X2 = -0.399*PC1 + 0.207*PC2-0.131*PC3 -0.503*PC4 + 0.197*PC5$ (2)

$X3 = 0.099*PC1 -0.853*PC2 -0.046*PC3 -0.04*PC4 + 0.039*PC5$ (3)

$Y_{force} = -0.256*PC1 + 0.313*PC2 -0.198*PC3 -0.907*PC4 + 0.385*PC5 -0.654*X1 -0.618*X2 + 0.241*X3$ (4)

The indirect effects from model 2 on tree-pulling variables were as follows:

$X1 = 0.179*PC1 -0.035*PC2 + 0.065*PC3 + 0.238*PC4 -0.095*PC5$ (5)

Y_{force} = 0.311*PC1-0.128*PC2-0.078*PC3 + 0.548*PC4-0.156*PC5 + 0.306*X2 + 0.047*X3 (6)

The total effects from model 2 on X1 and Yforce were as follows:

X1 = -0.063*PC1 -0.315*PC2 + 0.226*PC3 -0.379*PC4 + 0.066*PC5 -0.468*X2 -0.073*X3 (7)

Y_{force}= 0.055*PC1 + 0.1485*PC2-0.276*PC3-0.359*PC4 + 0.229*PC5-0.653*X1-0.312*X2 + 0.288*X3 (8)

Table 6
Regression weights of model 2 estimated by maximum likelihood method.

Path	Standardised weights	Std.Error	C.R.	P value
X1←PC1	-0.242	0.206	-1.173	0.241
X1←PC2	-0.28	0.35	-0.798	0.425
X1←PC3	0.161	0.18	0.897	0.37
X1←PC4	-0.617	0.217	-2.841	0.004
X1←PC5	0.161	0.183	0.879	0.379
X2←PC1	-0.399	0.16	-2.484	0.013
X2←PC2	0.207	0.16	1.291	0.197
X2←PC3	-0.131	0.16	-0.817	0.414
X2←PC4	-0.503	0.16	-3.134	0.002
X2←PC5	0.197	0.16	1.23	0.219
X3←PC1	0.099	0.116	0.846	0.397
X3←PC2	-0.853	0.116	-7.331	***
X3←PC3	-0.046	0.116	-0.392	0.695
X3←PC4	-0.04	0.116	-0.34	0.734
X3←PC5	0.039	0.116	0.335	0.738
Yforce←PC1	-0.256	0.173	-1.481	0.139
Yforce←PC2	0.313	0.288	1.085	0.278
Yforce←PC3	-0.198	0.149	-1.334	0.182
Yforce←PC4	-0.908	0.21	-4.326	***
Yforce←PC5	0.385	0.151	2.544	0.011
X1←X2	-0.468	0.252	-1.857	0.063
X1←X3	-0.073	0.347	-0.209	0.835
Yforce←X1	-0.654	0.186	-3.519	***
Yforce←X2	-0.618	0.222	-2.786	0.005
Yforce←X3	0.241	0.282	0.854	0.393

In Formula (8) from model 2, PC4 had a significant effect on total effect X1 (regression coefficient = -0.379) and total effect Y_{force} (regression coefficient = -0.359) with a negative effect. In terms of the standardised coefficient (absolute value) from formulas (7) and

(8), the effect rank of PCs on X1 from high to low was PC4 > PC2 > PC3 > PC5 > PC1, while that of Y_{force} was PC4 > PC3 > PC5 > PC2 > PC1. Repeatedly, PC4 was the most important factor affecting the stability of standing trees.

2.7 Goodness of fit

There were no single statistical test methods or parameters to evaluate a model of structural equation modelling (SEM); instead, different combined methods have been developed to assess the results. The commonly used fit indices in the literature include the CMIN, goodness of fit index (GFI), adjusted goodness of fit index (AGFI), comparative fit index (CFI), Tukey-Lewis index (TLI), normed fit index (NFI), incremental fit index (IFI), and root mean square error of approximation (RMSEA). GFI, AGFI, CFI, TLI, NFI, and IFI measures equal to or greater than 0.95, indicating that the model had a good fit. In addition, an RMSEA less than 0.05 displayed the most acceptable fitting index.

Table 7 shows that the fitting effect of the two models and the observed data was good, with P values of 1.000, and there was no significant difference (P > 0.05), indicating no significant difference between the observed values and the covariance matrix. Other goodness of fit indices (RMSEA = 0.000, GFI = 1.000, AGFI = 0.999, CFI = 1.000, NFI = 2.139, NFI = 1.000, IFI = 1.194) also showed that our models were acceptable, and the overall goodness of fit of the estimated model was good enough (Table 7).

Table 7
Summary of initial and final model fit.

Goodness-of-Fit Index	Recommended Value	Model 1	Model2	Fitness test
P value	Non-significant at p < 0.05	1.000	1.000	Yes
CMIN/DF	< 2	0.000	0.002	Yes
Root mean square error of approximation (RMSE)	< 0.08	0.000	0.000	Yes
Goodness-of-fit index (GFI)	> 0.90	1.000	1.000	Yes
Adjusted goodness-of-fit index (AGFI)	> 0.90	0.999	0.999	Yes
Comparative fit index (CFI)	> 0.90	1.000	1.000	Yes
Tucker-Lewis coefficient (TLI)	> 0.90	2.139	2.139	Yes
Normed fit index (NFI)	> 0.90	1.000	1.000	Yes
incremental fit index (IFI)	> 0.90	1.194	1.194	Yes

3. Discussion

Forest-based bioeconomy plays a crucial role in mitigating climate change [44], and wind damage is the most important factor causing forest damage [45]. The loss of wind damage to forestry is intensified with the ever-changing climate [5, 46, 47]. The wind and environment are difficult to predict, hence making useful measurements remains challenging. Therefore, data on how trees adapt to the wind environment [7, 48] and the associated physiological reaction remain limited. To effectively reduce the impact of wind damage on forestry, it is necessary to identify key factors that affect the sensitivity of trees/stands to wind damage [17].

In commercial forests, limited studies have investigated the differences in typhoon damage among various eucalyptus families [49, 50]. In our study, individual trees from 20 *E. camaldulensis* families over 3 years old were selected, and their growth traits, wood density, wood non-destructive testing traits, fibre morphological traits and its content, wood properties, and five wind damage indices were evaluated. The results showed significant differences between diverse *E. camaldulensis* families for all traits, while correlation analysis results showed that five type traits had a high correlation in the same type of traits and a certain degree of correlation between different types of traits. High correlations were observed between the wind damage indices and growth traits (H and VOL), PN and FL. The results showed that the growth, wood properties, and wind resistance of 20 *E. camaldulensis* families varied, which was consistent with the current research results [49]. The coefficient of variation and genetic analysis showed that the tested families had a higher coefficient of variation, indicating that tree wind resistance, like other traits, could be inherited and improved, making it possible to select better genotypes with good growth and wind resistance.

At present, the methods for evaluating or predicting wind damage can be divided into observation or experience, statistical, and mechanical methods [51]. Statistical methods use field observation data sets to simulate wind damage, past damage information and/or classify the vulnerability of specific forests [52]. It remains difficult to determine which factor is the most critical cause of wind damage [51], since the traits of standing trees are not independent of each other. In addition, tree wind resistance is a compound trait, hence it is necessary to use a variety of statistical methods to assess impact factors. Principal component analysis (PCA) is a multivariate statistical analysis method in which several variables were linearly transformed to select fewer important variables [53]. Therefore, we could effectively concentrate data and simplify indices to compensate for the deficiency of a single index in evaluating tree wind resistance. PCA of 17 traits other than wind damage index was further carried out and yielded five new independent comprehensive PC1-PC5 indices. The cumulative contribution rate was 80.230%, and the PCs could successfully extract relevant information in the trait data.

The static load test is currently the most advanced method for the assessment of tree stability. Static tree-pulling tests have been implemented on open-grown urban trees to measure the amount of force required to pull trees to failure [54, 55], test the effects of root loss on short-term tree stability [56], and estimate overall tree stability during tree risk assessments [57–59]. Therefore, in our study, the tree-pulling test was used to evaluate wind loads and its impact on tree stability, which better explains how various trees respond to wind.

CCA was used to assess the linear relationship between the two multidimensional variables [60]. A canonical correlation was applied to the same situation of multiple regression, but there were multiple interrelated outcome variables. Four tree-pulling variables, X1, X2, X3, and Y_{force}, which reflected the maximum Y_{force} in the tree-pulling test, were used to analyse the five PCs. CCA results showed that the top two canonical correlations reached 0.9547 and 0.9012, respectively ($P < 0.001$). Since canonical correlation reflected the variance shared by the linear combination of variable groups, it was difficult to identify the meaningful relationship between the subsets of independent and dependent variables, CCA does not always extract useful features [61]. In addition, there were obvious differences in wind resistance of *E. camaldulensis* families with various forest ages [49, 62] and in typhoon loading of individual trees. Therefore, the correlation between various traits and wind damage indices were not strong (Fig. 2). Insufficient correlation analysis and canonical correlation between traits and wind damage make obtaining the key traits impacting wind resistance challenging.

The proper selection of methodology is a crucial part of the research study [63, 64]. SEM is a second-generation multivariable method used to evaluate the reliability and validity of model measures, which is superior to the regression model [65, 66]. Path analysis, a precursor to and subset of SEM, can be used to discern and estimate the effects of a set of variables performing on a distinctive effect via a couple of causal pathways. The traditional path analysis with observed variables (PA-OV model) was an SEM without any potential variables [67], with all its variables being measurement variables. These measurement index variables are usually the sum of the scores of several measurement items in the scale rather than a single item. This study used the PA-OV model (model 1) for path analysis. In model 1, there was a correlation between the residual terms of variables (X1, X2, X3, and Y_{force}) obtained at the maximum pulling force. According to the actual situation and the causal relationship of all variables, model 2 was established based on model 1. In model 2, the explanatory variation of the four tree-pulling variables could be significantly improved; X1 and Y_{force}, where R^2 increased from 0.302 (model 1) to 0.410, and from 0.295 (model 1) to 0.614, respectively. The results of the effect analysis on tree-pulling variables showed that PC4 had a negative effect on the total effect of X1 (0.379) and Y_{force} (-0.359). PC4 affected the maximum values of X1 and Y_{force} in standing trees, namely, PC4 was the main factor affecting X1 and Y_{force} effects of trunk deformation. In summary, PC4 was the most important complex trait affecting the stability of standing trees.

When stem/branch fracture occurs, the tensile pressure caused by compression or moment is greater than the resistance of the wood fibre [68], the breakage can occur at tree trunk [69]. In other words, the traits reflected the fibre morphological and chemical composition, such as PC4 composed of FW, HC, and LC, is the key factor/trait that affect the tree wind resistance. This is consistent with the previous results corresponding to the lodging resistance of crops. The plant cell wall is composed of cellulose, hemicellulose, lignin, polysaccharides, and proteins, which form a strong network of filaments, providing mechanical support for cells, tissues, and the whole plant [70], which can reflect the plant anti-lodging ability to a certain extent [71]. Cellulose, as the main component of the cell wall, significantly promotes maintenance of the mechanical strength of the stem, while lignin can determine the strength of the cell wall and lodging resistance of the stem and plays an important role in maintaining the mechanical strength of the stem [72, 73]. The increase of cellulose level significantly improved the mechanical strength of the stem and increased the lodging resistance of wheat, rice, and soybean [74–76]. Lodging resistance in crops is directly proportional to the mechanical strength, and high lignin content can increase cell wall strength and mechanical strength [77, 78], which could be improved through the lignin accumulation [79–81]. Our results showed that although the trial forest had suffered three typhoons with a wind speed over 42 m/s, 1–5-year-old *Eucalyptus camaldulensis* stands/trees did not break or uproot. Our results are consistent with the claims of Albrecht et al. [28]. To minimise the loss of forest caused by wind damage, eucalyptus species/genotype with high cellulose and lignin content may be selected and targeted for forest production and management process in the typhoon-prone areas. Whether our findings are applicable to other tree species requires further research and verification.

4. Conclusion

Eucalyptus has high genetic heterozygosity, and many important traits such as growth and wood properties are quantitative and controlled by multiple genes [82, 83]. Similarly, tree wind resistance is caused by many complex traits. Wind damage and wind resistance of standing trees vary greatly due to the different varieties of eucalyptus and varied families from the same species at different ages under various environments. Therefore, in this study, a more efficient measurement technique and tree-pulling test was used to measure and estimate the wind resistance of different *E. camaldulensis* families.

This study identified that the key traits of PC4 comprised holocellulose content, lignin, and fibre width via path analysis. Our findings thus suggest that improving the traits for fibre morphology and content could enhance eucalyptus wind resistance and offer important insights for better eucalyptus management in the coastal area of South China.

5. Material And Methods

5.1 Experimental materials

Twenty genotypic materials were collected from 40-month-old, open-pollinated progeny trials of *E. camaldulensis* at the South China Experiment Nursery (21.263°N, 110.098°E), which is located in Suixi, Zhanjiang, Guangdong Province. The experimental forest was planted in August 2012, with a row spacing of 2 m × 3 m, 114 families in total, a completely randomised block design, and four repeats/block groups. Since planting, the experimental forest stand has been hit by five typhoons (Appendix A). Finally, 20 typical families (three replicates per family) were selected for the tree-pulling test. Specific information is shown in Table 8.

Table 8
Origin and code of tested varieties of *E. camaldulensis.* referred to Shang et al. [84]

No.	Family name[1]	Source of seedlot	Location[2]	Type[3]	Latitude	Longitude(E)	Altitude(m asl)	Mean annual rainfall(mm yr-1)
1	C04	India	DPK	CSO 1	-	-	-	-
2	C013	India	KUL	SSO 2	-	-	-	-
3	C014	India	DPK	CSO 1	-	-	-	-
4	C023	India	DPK	CSO 1	-	-	-	-
5	C033	India	DPK	CSO 1	-	-	-	-
6	C036	India	DPK	CSO 1	-	-	-	-
7	C046	India	MPM	CSO 1	-	-	-	-
8	C076	India	MPM	SSO 1	-	-	-	-
9	C079	India	MPM	SSO 1	-	-	-	-
10	C080	India	MPM	SSO 1	-	-	-	-
11	CA5	Australia	Laura River	NS	15º37' S	144º31’	95	988
12	CA7	Australia	Laura River	NS	15º37' S	144º31’	95	988
13	CA8	Australia	Laura River	NS	15º37' S	144º31’	95	988
14	CA9	Australia	Kennedy River	NS	15º23’ S'	144º10'	80	988
15	CA16	Australia	Morehead River	NS	15º02’ S	143º40’	60	1201
16	CA21	Australia	Palmer River	NS	16º07’ S	144º48’	410	1041
17	CA22	Australia	Palmer River	NS	16º07’ S	144º48’	410	1041
18	CA26	Australia	Normanby Rivers Normanby Rivers	NS	15º46’ S	144º59’	205	954
19	CA27	Australia	Normanby Rivers	NS	15º46’ S	144º59’	205	954
20	CA28	Australia	Normanby Rivers	NS	15º46’ S	144º59’	205	954

[1] Seedlots or Family names commencing with C were supplied by CSIRO’s Australian Tree Seed Centre.

[2] The exact locations of the C0 Indian seed orchards are uncertain. The three categories are : CSO: clonal seed orchard; SSO: seedling seed orchard; NS: natural stand.

[3]Type categories are: SSO = seedling seed orchard; CSO = clonal seed orchard; NS = natural stand.

5.2 Measurement indices and methods

The growth traits of tree height (H), DBH, and bark thickness (BT) were measured using a Vertex IV instrument (Haglof, Sweden), curled ruler, and ruler, respectively. Wind damage index (wind damage of standing tree, WD), based on that of Wang et al. [62], could be assessed subjectively using the following criteria: score 0, healthy tree, the trunk had no obvious inclination; score 1, low damage, the distance between trunk inclination and vertical was less than 30 degrees; score 2, low to moderate damage, the angle between trunk inclination and vertical was 30° to 60°; score 3, moderate damage, the angle between trunk inclination and vertical was 60° to 90°; score 4, high damage, the trunk lodging or uprooting; score 5, serious damage, the trunk or treetop was broken or failure. According to the time sequence of five typhoon attacks (Appendix A), the wind damage index of standing trees was recorded as WD1–WD5.

Pilodyn is a non-destructive testing instrument used for indirect determination of wood density. The Pilodyn tester can effectively and indirectly evaluate wood properties (such as strength and density) [85]. PILODYN 6J (PROCEQ company, Switzerland, probe diameter is 2.5 mm) was used to measure the DBH (height is 1.3 m) of the standing tree to obtain the Pilodyn reading value (Pilodyn penetration value, PN) associated with the standing tree density and strength. The propagation time of stress wave in 0.2–1.7 m high standing wood section was measured using a Fakopp microsecond timer (Fakopp Enterprise Bt, Hungary; repeated 5 times, and the average value is taken). The wood core was used to determine the fibre morphological characteristics collected at 1.3 m in the north-south direction of each tree using a tree growth cone (Swedish Haglof, inner diameter = 4.3 mm). The fibre length (FL) and fibre width (FW) were determined using an LDA 02 Hi-Res Fiber Quality Analyser (OPTEST, Canada) and the ratio of fibre length to fibre width (FLW) was calculated from the ratio of fibre length to fibre width.

In the tree-pulling test, an Argus PiCUS TreeQinetic tree stretching tester was used to simulate the wind damage. According to our previous experiences in the tree-pulling test (Appendix B), the trees were pulled at the height of 4 m, and then an elastometer and inclination metre were used to measure the elastic deformation and inclination angle of the trunk at the height of 2 m. Simultaneously, the pulling force of the cable was recorded. When the pulling force of the standing tree reached the maximum, the measured values of elastic deformation and inclination angle were recorded. The cable length from the pulling point of the tree to the anchor point and distance of the horizontal distance from the base of the tested tree to the anchor point were also recorded. The recorded parameters of the tree-pulling test were as follows: Y is the tension measured using a forcemeter (N), X1 is the deformation degree of the trunk measured using an elastometer (μm), X2 is the inclination angle of the trunk perpendicular to the pulling direction measured by the inclinometer (°), and X3 is the inclination angle of the trunk along the pulling direction (°).

After the tree-pulling test, the sample trees were cut down, and 2 sections of 2 m long log were cut off from 1.3 m height and numbered. When wood moisture content was approximately 12%, sample logs were prepared for the physical and mechanical determination of wood according to Chinese national standard GB 1929–2009 (Sawing and Sample cutting method of Wood material physical Mechanics). Wood basic density (WBD) was calculated according to Chinese national standard GB/T 1933–2009. The specific determination method was conducted according to Shang et al. [49], while the bending strength (MOR) was determined by testing the bending strength of wood (GB/T1936.1-2009 of Chinese national standards), and bending elastic modulus (MOE), was referenced the determination of the modulus of elasticity in static bending of wood (GB/T19362-2009 of Chinese national standards). The strength of structural timber parallel to grain (SSG) was evaluated by testing of shearing strength parallel to the grain of the wood (GB/T 1937–2009 of Chinese national standards). Compressive strength parallel to grain (CP) was determined by testing the compressive strength parallel to the grain of wood (GB/T 1935–2009 of Chinese national standards). MOR, MOR, SSG and CP were measured with an Instron 5582 type universal testing machine (Instron Corporation, USA). A total of 36 different size samples for physical and mechanical properties were tested. The Browning [86] method was used to determine the α-cellulose content (CC) and holocellulose content (HC). The Huntley method [87] was used to determine the lignin content (LC).

5.3 Data statistics and analysis

Microsoft Excel (version 2010 (Microsoft Corporation, 2021)) was used for collection, collation, and preliminary data analysis. R (version 4.0.3 (R Core Team, 2021)) and Rstudio (version 1.1.463 (R Studio Team, 2021)) were used to analyse the correlation, principal component analysis (PCA), and canonical correlation of the data. The stats19, canonical correlation analysis (CCA), CCP, ggplot2, and ggcorrplot packages were used for plotting. Because the data were the means of measurement, the standardised values were used for PCA and path analysis via IBM SPSS Amos software to eliminate the influence of different dimensions (version 24.0.0 (SPSS Inc., 2021)).

Abbreviations

DBH
diameter at breast height
H
tree height
VOL
volume of individual tree
BT
Bark thickness
WBD
Wood basic density
FL
Fibre length of wood
FW
Fibre width
FLW
Ratio of fibre length to fibre width
PN
Pilodyn penetration value determined by Pilodyn tester
FP
Readings of stress wave velocity tested by Fakopp microsecond timer
MOR
Bending strength of wood
MOE
Bending elastic modulus of wood
SSG
Strength of structural timber parallel to grain of wood
CP
Compressive strength parallel to grain of wood
CC
α-cellulose content
HC
Holocellulose content
LC
Lignin content
WD
Wind damage index scaled by wind damage of standing tree from different typhoon hit
Y_{force}
pulling force of the standing tree in tree-pulling test
X1
trunk deformation degree
X2
the inclination angle between the standing tree and the vertical direction of the tensile direction
X3
the inclination angle of the standing tree in the tensile direction

PCA
Principal component analysis
PC
Principal component
CCA
Canonical correlation analysis
CCP
Significance Tests for Canonical Correlation Analysis (CCA)
SEM
Structural equation modelling
PA
Path analysis
PA-OV
Path analysis with observation variable
CMIN
Value of chi-square
DF
Degrees of freedom
RMSE
Root mean square error of approximation
GFI
Goodness-of-fit index
AGFI
Adjusted goodness-of-fit index
CFI
Comparative fit index
TLI
Tucker-Lewis coefficient
NFI
Normed fit index
IFI
Incremental fit index

Declarations

Author contributions

SX and ZP: Conceptualisation, Methodology, Data curation, Project administration, Validation, Writing original draft, Writing - review & editing, Funding acquisition. **LG:** Data curation, Validation, Investigation. **WZ:** Methodology, Data curation, Supervision, Validation, Software, Writing - review & editing, Visualization. All authors read and approved the final manuscript.

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Consent for publication

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Availability of data and materials

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Competing interests

The authors declare that they have no competing interests.

Author details

[1]Research Institute of Fast-growing Trees, CAF, Zhanjiang 524022, Guangdong, China.

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Figures

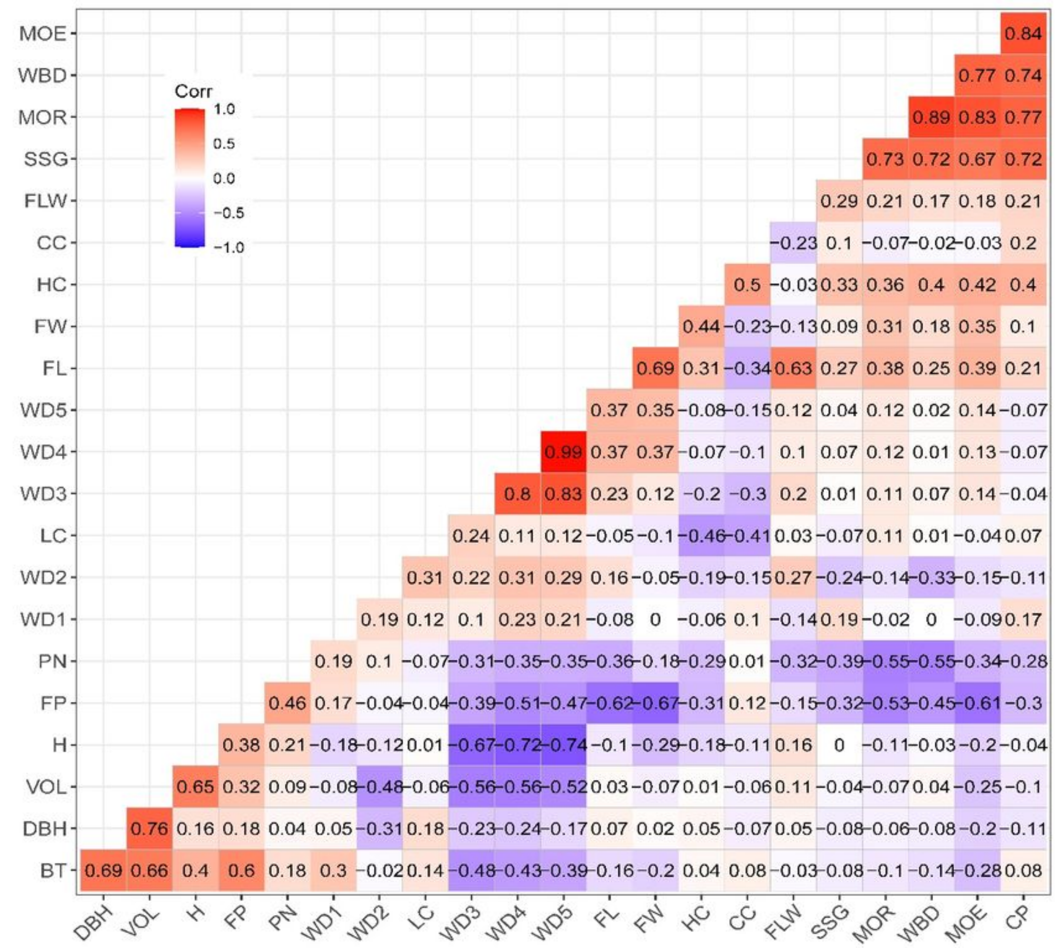

Figure 1

Correlation matrix of each traits. The number in the figure represents the correlation coefficient between two traits.

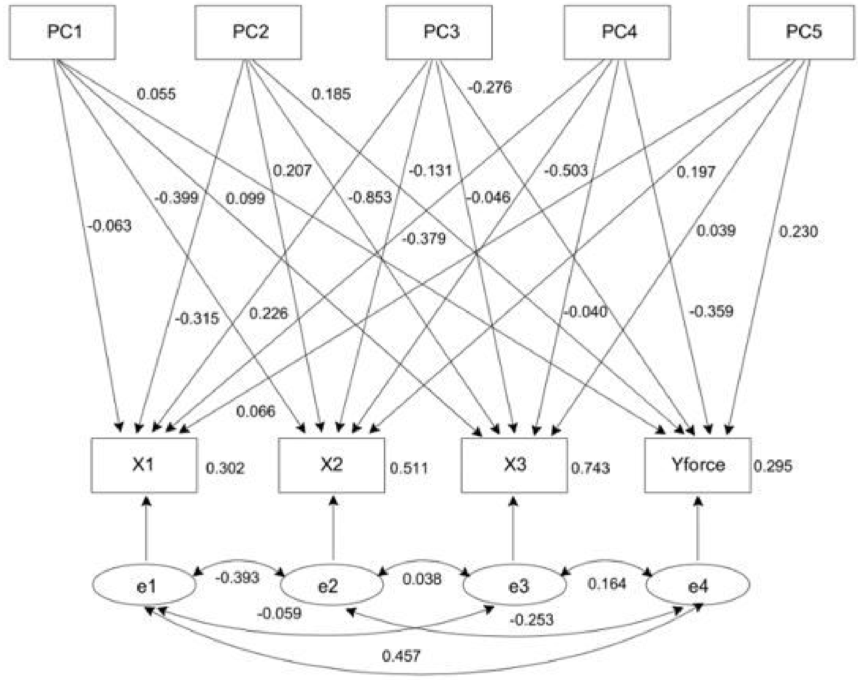

Figure 2

Path analysis of observed variables (Model 1)

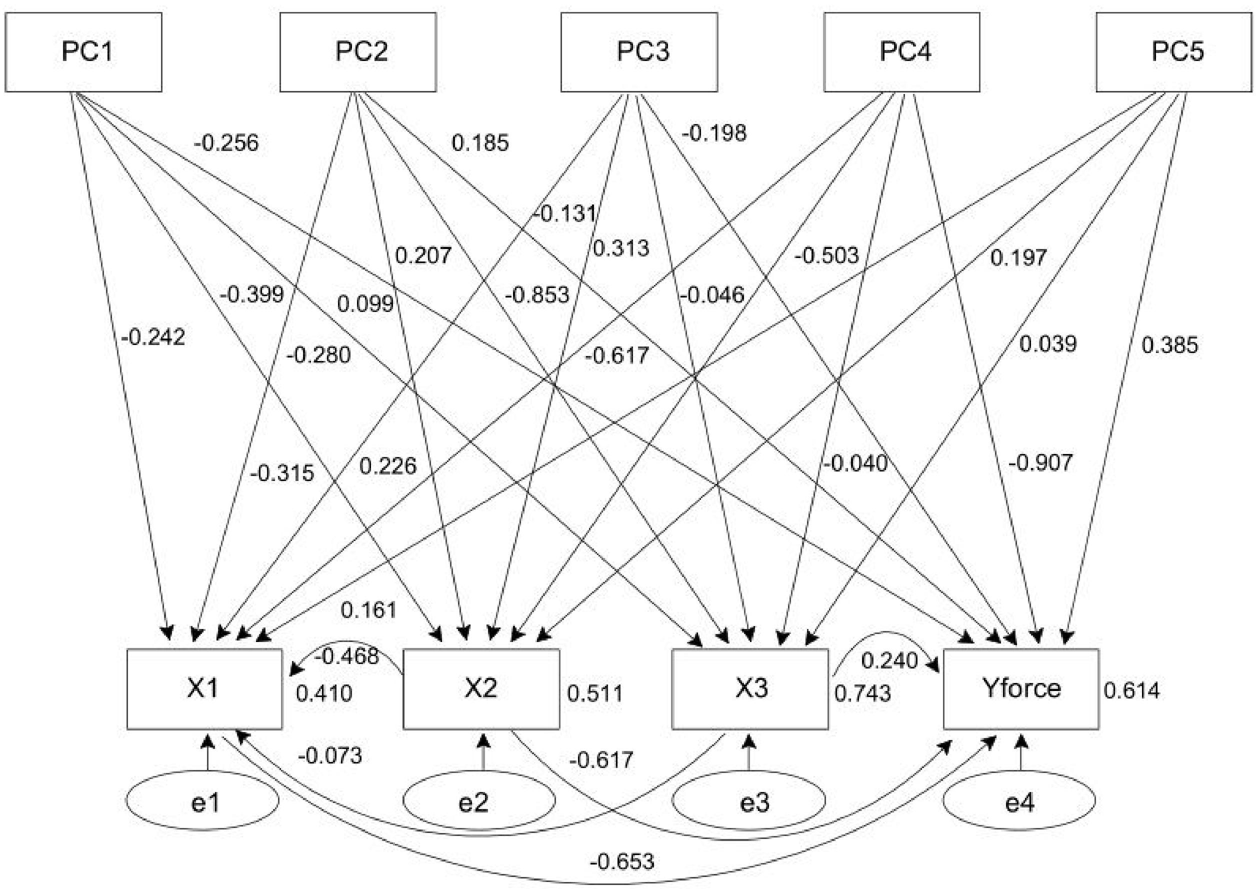

Figure 3

Path analysis of observed variables (model 2)

Supplementary Files

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- AppendixBSchematicdiagramofwinddamagetestfortreesimulation.docx
- AppendixCDifferentcharactersof20Eucalyptuscamaldulensisfamilies.docx
- AppendixDTensionofstandingtreesofC033familiesofEucalyptuscamaldulensis.docx
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