

ORIGINAL ARTICLE

Among-family variations in growth traits, the stress-wave velocity of stems, and log characteristics of the first-generation *Neolamarckia macrophylla* (Roxb.) Bosser in Indonesia

Umi Latifah Dyah Dharmawati¹, Ikumi Nezu¹, Futoshi Ishiguri^{1*}, Fanny Hidayati², Agus Ngadianto³, Yus Andhini Bhakti Pertiwi⁴, Arif Nirsatmanto⁵, Sri Sunarti⁵, Denny Irawati², Yusuke Takahashi⁶, Hikari Yokoyama¹, Jyunichi Ohshima¹ and Shinso Yokota¹

¹ School of Agriculture, Utsunomiya University, Utsunomiya 321-8505, Japan

² Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

³ Vocational College, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

⁴ Faculty of Agriculture, Universitas Sebelas Maret, Surakarta 57126, Indonesia

⁵ National Research and Innovation Agency, Yogyakarta 55281, Indonesia

⁶ Forest Tree Breeding Center, Forestry and Forest Products Research Institute, Hitachi 319-1301, Japan

* Corresponding author: ishiguri@cc.utsunomiya-u.ac.jp

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ABSTRACT The growth traits (stem diameter at 1.3 m above the ground and tree height), stress-wave velocity of the stems, and log characteristics (taper and dynamic Young's modulus of logs) were examined for 54 trees from 18 half-sib families planted in a seedling seed orchard of the first-generation *Neolamarckia macrophylla* (11-year-old) in Wonogiri, Central Java, Indonesia. The mean values for stem diameter and tree height were 20.2 cm and 20.0 m, respectively. The stress-wave velocity of the stems was 3.76 km s⁻¹. Meanwhile, the taper and dynamic Young's modulus of logs were 0.57 cm m⁻¹ and 8.13 GPa, respectively. The heritability values of each trait were 0.412, 0.365, 0.101, <0.001, and 0.092 for the stem diameter, tree height, stress-wave velocity of stems, taper of logs, and dynamic Young's modulus of logs, respectively, suggesting that the improvement of all traits is possible for the next generation, with the exception of the log taper. The 18 half-sib families could be classified into three groups for different potential uses based on the principal component analysis and cluster analysis results.

Key words: Fast-growing tree species, tree breeding, heritability, dynamic Young's modulus

INTRODUCTION

The demand for logs as raw materials in the wood industry in Indonesia has continued to increase over the years. Erwinsyah et al. (2017) estimated that the production of logs in Indonesia will increase by 0.61 to 3.32 % every year if the production of wood-based materials increases by 1 %. In 2022, Indonesian log production reached 64.65 million m³, and almost half of the production was from *Acacia* species, which are known as fast-growing tree species (Livestock, Fisheries, and Forestry Statistics 2023). This indicates that fast-growing species play a dominant role and potential in fulfilling the supply of wood demands in Indonesia. Cossalter and Pye-Smith (2003) reported that the mean annual increment at an operational scale and time

to reach maturity for the fast-growing tree species in temperate and tropical regions ranged from 5 to 40 m³ ha⁻¹ year⁻¹, and from 5 to 20 years, respectively. Therefore, logs from the fast-growing species can be obtained from the plantation within 20 years for Indonesia's wood industry.

Aside from *Acacia* species, several fast-growing species are found in Indonesia. For instance, *Neolamarckia macrophylla* (syn. *Anthocephalus macrophyllus* (Roxb.) Havil), known as jabon merah in Indonesian, that naturally distributed in eastern Indonesia, mainly in Sulawesi and the Maluku Islands (Irawan and Purwanto 2014). Halawane et al. (2011) reported that *N. macrophylla*, which grows naturally in Sulawesi has an annual radial growth rate of up to 7 cm year⁻¹ and a height of up to 3 m year⁻¹, indicating that it can reach 42 cm in stem diameter and 18 m in tree



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height at the age of six. Based on the data, they also estimated that the rotation age of plantations of this species might be 4 to 6 years, when intensive silvicultural treatment is applied (Halawane et al. 2011). In addition to its fast-growing characteristics, *N. macrophylla* has strong adaptability to various soil types and resistance to pests (Chung et al. 2016). Recently, these advantages have resulted in the establishment of plantations to supply wood for the industry.

To increase the potential of *N. macrophylla*, the Centre for Forest Biotechnology and Tree Improvement in Indonesia has conducted a tree breeding program for this species. In the program, 55 superior mother trees were selected based on their growth traits (stem diameter, tree height, and disease resistance) from Konawe, Southeast Sulawesi, Indonesia. Using the seeds from the mother trees selected, a seedling seed orchard was established as the first-generation trial test site in Wonogiri, Central Java, Indonesia, in 2012 (Setyaji et al. 2012). After establishing the test site, several studies concerning growth traits were conducted at a young age (Surip et al. 2017; Hidayati et al. 2020; Ihda et al. 2023). For example, Surip et al. (2017) reported that the score for stem straightness in 40-month-old trees was 2.74, demonstrating good straightness. The bark thickness of 5-year-old *N. macrophylla* was 0.36 cm (Ihda et al. 2023); meanwhile, the stem diameter and tree height were 18.4 cm and 15.4 m, respectively (Hidayati et al. 2020). Unfortunately, the wood traits are not yet fully clarified for the breeding materials of this species. Thus, wood traits of this species should be clarified to create the next generation with favorable wood traits for the wood industry as well as the pulp and paper industry in Indonesia.

In the present study, growth traits (stem diameter at 1.3 m above the ground and tree height) were evaluated in 54 trees from 18 half-sib families planted in a seedling seed orchard of the first-generation *N. macrophylla* in Wonogiri, Central Java, Indonesia. Stress-wave velocity, which is closely related to Young's modulus of wood, was also measured on the stems. In addition, longitudinal variations of log characteristics (log taper and dynamic Young's modulus) were evaluated for the harvested trees. Based on the results, among-family variations and the heritability of each trait were estimated to investigate the possibility of selecting candidates for the next generation. Furthermore, a principal component analysis and a cluster analysis were conducted to investigate the broader utilization of the wood from this species.

MATERIALS AND METHODS

Field data collection

This study was conducted using the 11-year-old trees planted in a seedling seed orchard of *Neolamarckia macrophylla* (Roxb.) Bosser (syn. *Anthocephalus macrophyllus*) located in Wonogiri, Central Java, Indonesia (07° 48' S, 110° 54' E; 141 m above sea level; Fig. 1). The site was the first-generation seedling seed orchard of this species, with 55 half-sib families originating from Konawe, Southeast Sulawesi, Indonesia. The 7-month-old seedling was planted in the seedling seed orchard in February 2012 with randomized complete block designs, including eight replications (blocks I to VIII). Each family was represented by four trees in a one-row plot per block. The initial planting spacing was 4 by 2 m. At age 5, thinning treatment was conducted in blocks I, II, III, and IV. As a result, one tree in each family in a block remained. On the other hand, thinning treatment did not apply to blocks V to VIII. The climate conditions of the progeny trial site are presented in Fig. 1.

In July 2023, stem diameter was measured in total of 220 trees (1 tree by 55 families by 4 blocks) in blocks I to IV. According to the mean (μ) and standard deviation (SD) of the stem diameter (d) in blocks I to IV, families were classified into three growth categories: slow growth ($d < \mu - SD$), medium growth ($\mu - SD \leq d < \mu + SD$), and fast growth ($d \geq \mu + SD$). Six families from each growth category were selected. Sample trees were then chosen from the trees of the selected families growing in unthinned blocks (V to VIII). Among 16 trees (four trees in a one-row plot per block by four blocks) of each family in four blocks (V to VIII), three trees were selected based on their stem diameter ranking: Trees with second to fourth stem diameter ranking were selected, since the best tree must remain as a seed source in the seedling seed orchard. As a result, 54 sample trees from 18 families were selected in blocks V to VIII for measuring the growth and wood traits.

The stem diameter at 1.3 m above the ground and the tree height were measured for each tree using a diameter tape (Mejiro, Japan) and a Vertex III instrument (Haglöf, Sweden), respectively. The stress-wave velocity of the stem was measured on standing trees using a commercial handheld stress-wave timer (Fakkop Microsecond Timer, Fakkop Enterprise, Hungary). According to the methods of the previous research by Ishiguri et al. (2008), the start and stop sensors were installed at heights of 1.5 m and 0.5 m above ground, respectively. The stress-wave propagation time was measured six times at the same stem position by

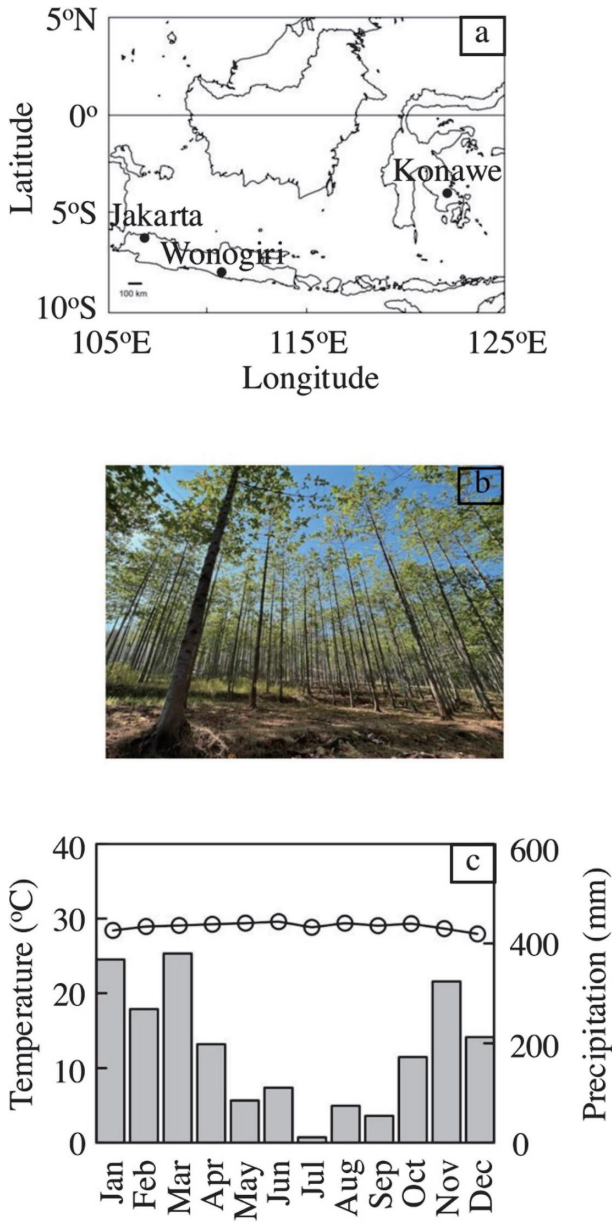


Fig. 1. Location (a), a photograph (b), and climate data (c) of the sampling site.

Note: Konawe, Southeast Sulawesi, Indonesia is the location of the origin of the mother trees. Wonogiri, Central Java, Indonesia is the location of the seedling seed orchard used in the present study. Jakarta is the capital city of Indonesia (Fig. 1a). The mean monthly temperature and monthly precipitation (Fig. 1c) were calculated by averaging monthly values from 2018 to 2022 (Statistics of Wonogiri Regency 2023). In Fig. 1c, bars indicate the mean value of precipitation, and circles indicate the mean value of the monthly mean temperature.

hitting the start sensor with a hammer. The stress-wave velocity was then calculated by dividing the distance between two sensors by the average time of the six time measurements.

The trees were harvested to collect the wood samples after measuring the tree characteristics. The 2-meter-long logs were collected from 1.3 m to 7.3 m above the ground (three logs were obtained from each tree) from harvested trees. The dynamic Young's modulus of logs was determined by the longitudinal vibration method according to previous researches (Sobue 1986; Ishiguri et al. 2021). A small hammer hit the cross-section of the butt end to create sound waves. The first resonance frequency was measured at the cross-section of the top end using a clip-on microphone (Fantech, Indonesia) and an application (sound monitor FFT Wave application, E.N. Software, Japan) installed in a smartphone (Galaxy A20, Samsung, South Korea). Before measuring the frequency, the diameters of both cross ends (including bark) and the length and weight of the logs were measured using a diameter tape (Mejiro, Japan), a measuring tape (Joyko, Indonesia), and an electronic balance (Wesco digital scale, Indonesia), respectively, to calculate the density of the logs during testing. The dynamic Young's modulus (E_{jt} , GPa) of logs was calculated using the following equation:

$$E_{jt} = (2lf)^2 \cdot \rho \cdot 10^{-9} \quad (1)$$

where l is the length of the specimen (m), f is the first resonance frequency (Hz), and ρ is the density of logs at testing (kg m^{-3}).

Statistical analysis

The statistical analysis was performed using the statistical software R 4.3.2 version (R Core Team 2023). Following intercept-only and linear mixed-effects models with random effects of the family were developed to evaluate longitudinal variations of log characteristics using the package "lme4" (Bates 2022):

$$Y_j = \mu + e_j \quad (2)$$

$$Y_{jk} = \mu + \text{Family}_{jk} + e_{jk} \quad (3)$$

$$Y_{ij} = \alpha_0 X_{ij} + \alpha_1 + e_{ij} \quad (4)$$

$$Y_{ijk} = (\alpha_0 + \text{Family}_{0k}) X_{ijk} + \alpha_1 + e_{ijk} \quad (5)$$

$$Y_{ijk} = \alpha_0 X_{ijk} + \alpha_1 + \text{Family}_{1k} + e_{ijk} \quad (6)$$

$$Y_{ijk} = (\alpha_0 + \text{Family}_{0k}) X_{ijk} + \text{Family}_{1k} + \alpha_1 + e_{ijk} \quad (7)$$

where Y_j is the measured property of the j th individual tree, Y_{jk} is the measured property of the j th individual tree within the k th family, Y_{ij} is the measured property of the i th height

position at the top end of the log (m above the ground) of the j th individual tree, Y_{ijk} is the measured property of the i th height position at the top end of the log (m above the ground) of the j th individual tree within the k th family, μ is the grand mean, X_{ij} is the i th height position at the top end of the log (m above the ground) of the j th individual tree, X_{ijk} is the i th height position at the top end of the log (m above the ground) of the j th individual tree within the k th family, α_0 is the fixed slope, α_1 is the fixed intercept, $Family_k$ is the random effect of the k th family, $Family_{0k}$ and $Family_{1k}$ are the random slope and intercept of the k th family, and e_j, e_{jk}, e_{ij} and e_{ijk} are residuals. The model with the minimum Akaike Information Criterion (AIC) (Akaike 1998) was regarded as the optimal model among the developed models. When the model including the random effects of the family (Eqs. [3], [5], [6], and [7]) was selected as the optimal model, the variance component ratio of the family was calculated using the following formula:

$$V_f^2 = \sigma_f^2 / (\sigma_f^2 + \sigma_e^2) \cdot 100 \quad (8)$$

where V_f^2 (%) is the variance component ratio of the family, σ_f^2 is the variance component of the family, and σ_e^2 is the residual variance.

To estimate the broad-sense heritability of each trait, the variance components of the family for the growth and wood traits were estimated using the following linear mixed-effects model (9):

$$y_{jk} = \mu + Family_k + e_{jk} \quad (9)$$

where y_{jk} is the individual mean of the growth and wood traits of the j th individual tree at the k th family, μ is the ground mean, $Family_k$ is the random effect of the k th family, and e_{jk} is residual. The broad-sense heritability of each trait was estimated by the genetic variance using the following formula provided by Falconer and Mackay (1989):

$$H^2 = \sigma_f^2 / (\sigma_f^2 + \sigma_e^2) \quad (10)$$

where H^2 is broad-sense heritability, σ_f^2 is the variance component of the family, and σ_e^2 is the residual variance.

Using the random effect values of the families estimated by the model (9), a principal component analysis (PCA) was performed. A cluster analysis was conducted using the PCA scores for principal component (PC)1 and PC2 to categorize the families according to their potential utilization. Subsequently, the phenotypic correlations (r_p) were determined for the measured traits. In addition, the genetic correlations (r_g) were calculated using random-effect estimates for family obtained from Eq. (9) by Pearson's correlation coefficients.

RESULTS

The mean values of the growth and wood traits of 18 half-sib families *Neolamarckia macrophylla* are presented in Tables 1 and 2. The stem diameter ranged from 14.5 cm in family number 34 to 28.3 cm in family number 70. The total mean value of the stem diameter from 54 trees was 20.2 cm. The minimum mean value of tree height was recorded in family numbers 48 and 50 (17.8 m), while the maximum mean value was in family number 70 (22.9 m). The total mean value of tree height was 20.0 m.

The stress-wave velocity ranged from 3.60 km s⁻¹ in family numbers 50 and 59 to 3.94 km s⁻¹ in family number 22, with a total mean value of 3.76 km s⁻¹. The mean values of the dynamic Young's modulus of logs ranged from 7.53 GPa in family number 59 to 9.20 GPa in family number 30, with a total mean value of 8.13 GPa.

Table 2 shows the values of the taper and dynamic Young's modulus of logs, which were used to evaluate their longitudinal variations using mixed-effects models. Based on the AIC values (Table 3), the intercept-only model (Eq. [2]) was selected for the longitudinal variation of the log taper, and the longitudinal variation of dynamic Young's

Table 1. Mean values of stem diameter, tree height, and stress-wave velocity of stems in 18 half-sib families.

Family ID	<i>n</i>	Stem diameter (cm)	Tree height (m)	Stress-wave velocity (km s ⁻¹)
22	3	21.2	21.2	3.94
26	3	17.0	17.9	3.68
30	3	25.3	21.5	3.85
32	3	18.2	21.4	3.89
34	3	14.5	18.6	3.63
36	3	19.0	18.5	3.87
43	3	20.0	21.6	3.78
48	3	15.0	17.8	3.73
50	3	17.9	17.8	3.60
57	3	19.2	19.0	3.71
58	3	17.8	19.1	3.92
59	3	24.6	21.7	3.60
61	3	20.0	20.8	3.65
65	3	16.4	18.0	3.81
70	3	28.3	22.9	3.66
82	3	22.4	20.9	3.81
103	3	26.9	22.4	3.82
113	3	19.4	18.8	3.77
Minimum		12.9	16.1	3.45
Maximum	54	37.6	25.0	4.17
Mean ± SD		20.2 ± 5.0	20.0 ± 2.3	3.76 ± 0.17

Note: *n*, number of trees; SD, standard deviation.

Table 2. Mean values of taper and dynamic Young's modulus of logs in 18 half-sib families.

Family ID	<i>n</i>	First log		Second log		Third log		Mean	
		Taper (cm/m)	DMOE (GPa)	Taper (cm/m)	DMOE (GPa)	Taper (cm/m)	DMOE (GPa)	Taper (cm/m)	DMOE (GPa)
22	3	0.26	8.53	1.04	8.54	0.51	8.76	0.61	8.61
26	3	0.79	7.33	0.43	7.65	0.34	8.36	0.52	7.78
30	3	1.08	9.38	0.00	9.14	0.86	9.09	0.65	9.20
32	3	0.70	8.58	0.53	8.89	0.61	9.85	0.61	9.11
34	3	0.35	7.85	0.35	8.45	0.61	8.60	0.43	8.30
36	3	0.17	7.65	0.43	7.99	0.26	8.99	0.29	8.21
43	3	0.56	7.50	0.26	7.57	0.63	8.11	0.48	7.73
48	3	0.78	7.28	0.60	8.17	0.27	7.69	0.55	7.71
50	3	0.95	7.54	0.52	7.81	0.69	8.10	0.72	7.82
57	3	0.69	7.46	0.70	8.18	0.52	7.87	0.63	7.84
58	3	0.60	7.94	0.71	8.30	0.35	7.97	0.55	8.07
59	3	0.54	7.56	0.87	7.39	0.61	7.65	0.67	7.53
61	3	0.96	7.82	0.43	8.62	0.97	9.28	0.79	8.57
65	3	0.95	7.69	0.61	8.17	0.60	7.99	0.72	7.95
70	3	0.54	7.83	0.17	7.55	0.52	7.87	0.41	7.75
82	3	0.35	7.67	0.56	7.71	0.89	8.27	0.60	7.88
103	3	0.82	7.43	0.89	8.40	0.35	8.10	0.69	7.97
113	3	0.17	8.05	0.68	8.23	0.43	8.61	0.43	8.30
Minimum		0.00	6.43	0.00	5.96	0.00	6.63	0.29	7.53
Maximum	54	1.67	11.17	1.91	10.52	2.14	11.21	0.79	9.20
Mean $\pm$ SD		0.63 $\pm$ 0.28	7.84 $\pm$ 0.53	0.54 $\pm$ 0.26	8.15 $\pm$ 0.48	0.56 $\pm$ 0.21	8.40 $\pm$ 0.60	0.57 $\pm$ 0.13	8.13 $\pm$ 0.46

Note: *n*, number of trees; DMOE, dynamic Young's modulus of logs; SD, standard deviation.

Table 3. Values of Akaike Information Criterion (AIC) in the models for longitudinal variations of taper and dynamic Young's modulus of logs.

Trait	Equation					
	(2)	(3)	(4)	(5)	(6)	(7)
Taper of logs	165.29	–	166.32	–	–	–
Dynamic Young's modulus of logs	427.97	421.14	418.84	415.85	414.54	–

Note: Data for taper and dynamic Young's modulus of logs are at different height positions. The bold values indicate the selected model with a minimum AIC value; –, the model failed to converge.

modulus was well-fitted to the linear mixed-effects model, which includes random intercepts of the family (Eq. [6]). The taper was stable, while the dynamic Young's modulus was increased from base to top (Fig. 2). The regression lines in Fig. 2 were based on the fixed-effect parameters in the selected models (Table 4).

The variance component and broad-sense heritability of the growth and wood traits obtained in this study are presented in Table 5. The heritability values of the stem diameter, tree height, stress-wave velocity of the stems, and dynamic Young's modulus of logs were 0.412, 0.365, 0.101, and 0.092, respectively. Meanwhile, the heritability value

of the taper was nearly zero.

The phenotypic correlations (r_p) between the measured traits are presented in Table 6. Positive significant correlations were found between the stem diameter and tree height ($r_p = 0.528$, $p < 0.001$) and between the stress-wave velocity of the stems and the dynamic Young's modulus of logs ($r_p = 0.352$, $p = 0.009$). However, no correlations were found between the growth and wood traits.

Similar results were found in terms of genetic correlations (r_g) (Table 6). A positive correlation was found between stem diameter and tree height ($r_g = 0.844$, $p < 0.001$). The stress-wave velocity of the stems was also correlated with

the dynamic Young's modulus of logs ($r_g = 0.509$, $p = 0.031$), yet no correlations were found between growth and wood

traits.

The results of the principal component analysis of the random effect of family for the measured traits are presented in Fig. 3 and Table 7. The cumulative proportion of variance in PC1 and PC2 was 48.6 % and 35.5 %, respectively (Fig. 3). High loading values in PC1 were shown for stem diameter and tree height (0.606 and 0.662, respectively), whereas in PC2, the high absolute values were shown for the stress-wave velocity and dynamic Young's modulus of logs (-0.636 and -0.622 , respectively) (Table 7). Based on the

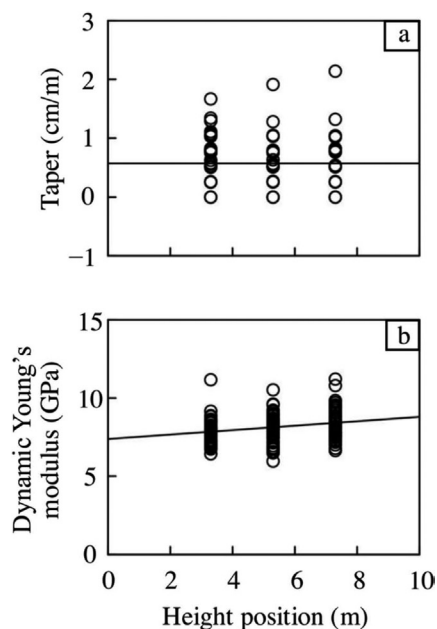


Fig. 2. Longitudinal variations of taper (a) and dynamic Young's modulus (b) of logs in 54 individual trees of 18 half-sib families.

Note: Regression lines were based on the fixed-effects parameters in the selected model in Table 4.

Table 6. Correlations between measured traits.

Trait 1	Trait 2	Phenotypic		Genetic	
		r_p	p -value	r_g	p -value
D	TH	0.528	<0.001	0.844	<0.001
	SWV	-0.129	0.353	0.029	0.901
	DMOE	-0.151	0.275	0.021	0.933
TH	SWV	-0.106	0.444	0.151	0.550
	DMOE	0.126	0.364	0.217	0.387
SWV	DMOE	0.352	0.009	0.509	0.031

Note: D, stem diameter; TH, tree height; SWV, stress-wave velocity of stems; DMOE, dynamic Young's modulus of logs; r_p , phenotypic correlation coefficient; r_g , genetic correlation coefficient. Number of trees in phenotypic correlations is 54. Number of families in genetic correlations in the Eq. (9) is 18.

Table 4. Parameter estimates, standard errors, t -values, and p -values of fixed-effect parameters and variance components for a selected model of taper and dynamic Young's modulus of logs.

Trait	Eq.	Fixed-effect parameter					Variance component		$V^2_f(\%)$
		Parameter	Estimate	SE	t -value	p -value	σ^2_f	σ^2_e	
Taper	2	μ	0.573	0.032	18.160	<0.001	—	—	—
DMOE	6	a_0	0.142	0.039	3.719	<0.001	0.1565	0.6205	20.2
		a_1	7.377	0.231	31.890	<0.001			

Note: DMOE, dynamic Young's modulus of logs; μ , grand mean; a_0 , fixed slope; a_1 , fixed intercept; SE, standard errors; σ^2_f , variance component of family; σ^2_e , residual variance; $V^2_f(\%)$, variance component ratio of family.

Table 5. Variance components and broad-sense heritability in each measured trait.

Trait	Variance component			Heritability
	σ^2_f	σ^2_e	Total	
Stem diameter	10.530	15.050	25.580	0.412
Tree height	1.940	3.372	5.312	0.365
Stress-wave velocity of stems	0.003	0.027	0.030	0.101
Taper of logs	<0.001	0.057	0.057	<0.001
Dynamic Young's modulus of logs	0.053	0.524	0.577	0.092

Note: ; σ^2_f , variance component of family; σ^2_e , residual variance.

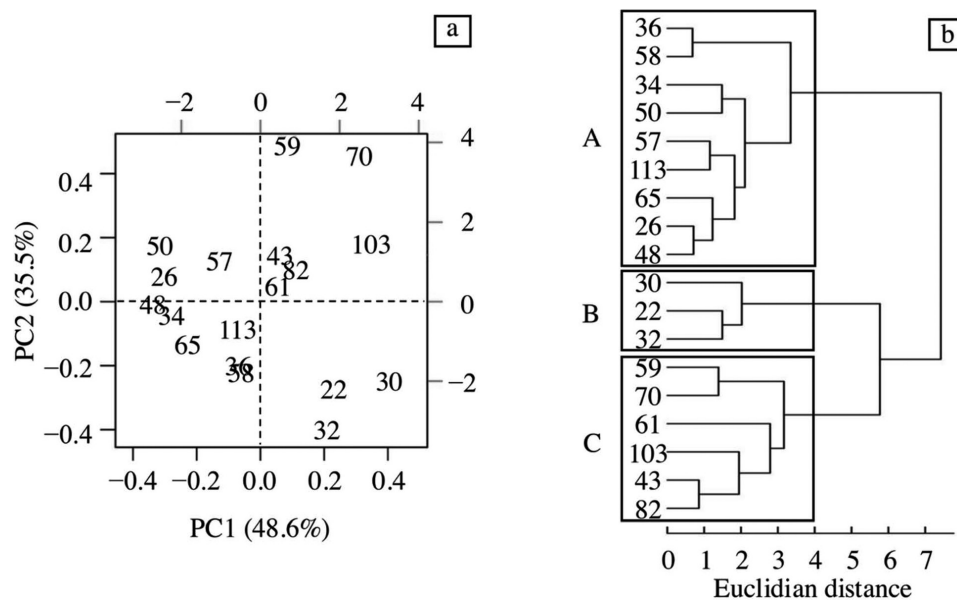


Fig. 3. Principal component analysis plot (a) and dendrogram (b) based on the principal component scores.

Note: PC, principal component. Numbers in Figs. indicate family IDs. Alphabets indicate cluster groups. Boxes indicate families in the same group.

Table 7. Loading values of principal component analysis for 18 half-sib families.

Trait	PC1	PC2
Stem diameter	0.606	0.392
Tree height	0.662	0.235
Stress-wave velocity of stems	0.299	-0.636
Dynamic Young's modulus of logs	0.326	-0.622

Note: PC, principal component.

Table 8. Characteristics of each group.

Cluster	Growth trait	Wood trait	Description	Expected utilization
A	+	++	Medium wood traits but poor growth traits	Solid wood production for non-structural use
B	+++	+++	Superior families both growth and wood traits	Candidate of the next generation producing solid wood for structural use
C	+++	++	Good growth traits with lower wood traits	Biomass production, veneer production, and pulp and paper production

Note: +++, very good; ++, average; +, poor; cluster A to C refer to Fig. 3.

principal component analysis scores, 18 half-sib families were classified into three groups (Fig. 3), and the potential utilization of each group was examined in Table 8.

DISCUSSION

Growth and wood traits

The annual radial growth rates (stem diameter / tree age) in the present study ranged from $1.32 \text{ cm year}^{-1}$ (14.5 cm / 11 years) to $2.57 \text{ cm year}^{-1}$ (28.3 cm / 11 years), lower than

the annual radial growth rate of *N. macrophylla* from the same seedling seed orchard at 3 years old, which was 4.4 cm year^{-1} ($13.2 \text{ cm} / 3 \text{ years}$) (Surip et al. 2017); and also 5-year-old trees reported by Hidayati et al. (2020), $2.70 \text{ cm year}^{-1}$ ($13.5 \text{ cm} / 5 \text{ years}$) to $4.30 \text{ cm year}^{-1}$ ($21.5 \text{ cm} / 5 \text{ years}$). In another study, the annual radial growth rate of 4-year-old trees grown in Gorontalo was $3.32 \text{ cm year}^{-1}$ ($13.3 \text{ cm} / 4 \text{ years}$) to $3.64 \text{ cm year}^{-1}$ ($14.6 \text{ cm} / 4 \text{ years}$) (Sandalayuk et al. 2023). These results suggest that the annual radial growth rate in the present study is slower than that in the previous studies. On the other hand, the radial growth rate is usually not equal during tree life: The rate appeared fast at younger ages, and then became slow as tree age increased (Salas-Eljatib et al. 2021; Nezu et al. 2023). In 12-year-old *Eucalyptus camaldulensis* planted in Thailand, the mean annual increment gradually decreased from younger ages up to 12 years of age (Nezu et al. 2023). Considering that the expected harvesting period in *N. macrophylla* is 4 to 6 years, the radial growth rate after 4 to 6 years of planting might become slow, leading to the slower annual radial growth rate obtained in the present study ($1.32 \text{ cm year}^{-1}$ to $2.57 \text{ cm year}^{-1}$ for 11-year-old trees) compared to other previous research results. Further research is needed to clarify the age-related changes in the radial growth rate of this species.

Compared to other fast-growing species, the dynamic Young's modulus of logs in the present study was lower than for *Acacia mangium* (11.70 GPa, Ngadiano et al. 2020) and *Eucalyptus camaldulensis* (11.72 GPa, Ishiguri et al. 2013), although the stress-wave velocity of stems was similar (*A. mangium* = 3.60 to 3.77 km s^{-1} , Masendra et al. 2023; *E. camaldulensis* = 3.45 km s^{-1} , Ishiguri et al. 2013). These differences might be due to differences in measuring methods between the dynamic Young's modulus of logs and the stress-wave velocity of stems, and in radial variations of wood properties, such as wood density and microfibril angle (MFA). On the other hand, Pertiwi et al. (2017) reported that the stress-wave velocity of stems and the dynamic Young's modulus of logs in 4-year-old *Neolamarckia cadamba* trees planted in Indonesia were 2.99 km s^{-1} and 6.54 to 6.64 GPa , respectively. Thus, Young's modulus of logs and the stress-wave velocity of stems in *N. macrophylla* might have a higher value than those in *N. cadamba* (Pertiwi et al. 2017), although the tree age differed.

The broad-sense heritability of stem diameter and tree height in the present study (Table 5) was similar to the heritability values at the family level for 55 half-sib families of *N. macrophylla* (0.463 for stem diameter and 0.213 for

tree height; Surip et al. 2017). The heritability of growth traits in this study showed similar or relatively higher values compared to the previous study (Surip et al. 2017). Thus, growth characteristics can be improved through the selection of superior families under appropriate tree breeding programs. Although the heritability showed lower values for stress-wave velocity and dynamic Young's modulus of logs than growth characteristics, the heritability was around 0.1, suggesting that wood traits also might be genetically improved through family or within-family selection in this species.

Longitudinal variations of log characteristics

The selected model explaining the longitudinal variation of the log taper was an intercept-only model (Eq. [2], Table 3), indicating that the taper values were almost stable from the base to the top (Fig. 2). In general, trees show that forcing the crown up the stem by pruning decreases the taper (Punches 2004). Halawane et al. (2011) reported that *N. macrophylla* has self-pruning abilities. Thus, this ability might reduce the taper due to the uniform growth along the stem of this species. On the other hand, the selected model in the taper (Eq. [2]) did not include the random effect of family. These results suggest that the stem form of the *N. macrophylla* tree is cylindrical, despite the differences between the families. In addition, the heritability of the log taper was almost zero (Table 5). Based on these results, the log taper of this species might be improved by the silvicultural treatments, such as by controlling the crown size by pruning and changing the tree spacings.

The fixed slope α_0 was 0.142 in the selected model of the dynamic Young's modulus of logs (Table 4), suggesting that the dynamic Young's modulus slightly increased from the base to the top in *N. macrophylla* (Fig. 2). Young's modulus of wood is closely related to the wood density (Saranpää 2003) and the MFA in the S2 layer of tracheids and wood fibers (Donaldson 2008). Thus, the increase of the dynamic Young's modulus of logs in this study might be due to a higher wood density or a lower microfibril angle (MFA) along the stem. Further research is needed to clarify the effects of wood density and MFA on Young's modulus of wood and on radial variations of wood density and MFA in *N. macrophylla*.

The selected model explaining the dynamic Young's modulus of logs (Eq. [6], Table 3) included a random intercept of the family, suggesting that the ranking at the family levels in the dynamic Young's modulus of logs might be the same at each height position. In addition, the

random slope of the family was not included in Eq. (6) for the dynamic Young's modulus, indicating that the increasing ratio from the base to the top might be almost the same among families. Furthermore, the variance component of the family was moderate (ca. 20 % in Table 4). Therefore, selecting the families with a high dynamic Young's modulus in the first logs might lead to the effective utilization of the *N. macrophylla* wood as solid wood.

Relationships between traits

Table 6 indicates a positive correlation between the stress-wave velocity of stems and the dynamic Young's modulus of logs. The same results were reported in previous studies (Ishiguri et al. 2008, 2021): The stress-wave velocity of stems has a positive correlation with the log's dynamic Young's modulus. Thus, the stress-wave velocity on a standing tree can predict the Young's modulus of a log, even if the stress-wave velocity might only be measured at outer parts of the stems.

The positive correlations, both phenotypic (r_p) and genetic (r_g), between the stem diameter and tree height and between stress-wave velocity of stems and the dynamic Young's modulus of log might provide a more straightforward selection process. Considering their heritability, the stem diameter and stress-wave velocity of stems are easier to measure in the field. Thus, these two traits (stem diameter and stress-wave velocity of stems) can be used as selection criteria to increase genetic gain.

Characterization of families

According to Halawane et al. (2011), *N. macrophylla* is commonly used as plywood, pulp and paper, boards, crates, furniture, and non-construction building materials. In the present study, based on the cluster analysis according to the principal component analysis (Table 7 and Fig. 3), the families were divided into three groups. The characteristics and potential utilization of each group are presented in Table 8. The families in group A exhibited average values in wood traits but had below-average growth traits. The wood from families in group B is considered superior because they have the best growth and wood traits among the other families. Thus, the families within group B may be candidates for the next generation to improve the growth and wood traits of *N. macrophylla*. The wood within these families can be used for solid wood production for structural purposes. On the other hand, group C has very

good growth traits. The wood within the families in group C is suitable as raw material for pulp and paper or biomass products. In addition, the moderate decrease in diameter of this species suggests that the stem shape is relatively cylindrical based on its taper values (Table 2), allowing this wood to be utilized as a raw material for veneer because it can produce a high yield.

CONCLUSION

The growth traits, stress-wave velocity of the stem, and dynamic Young's modulus of logs were evaluated for 18 half-sib families of the 11-year-old first-generation *N. macrophylla* grown in Central Java, Indonesia. Positive significant relationships were found between stem diameter and tree height, and between the stress-wave velocity of stems and the dynamic Young's modulus of logs. Thus, the stem diameter and stress-wave velocity on standing trees can be powerful tools for selecting the criteria of superior trees in the tree breeding program for this species. No significant correlation was found between growth traits and wood traits. According to broad-sense heritability and the correlation between measured traits, both growth and wood traits can be improved simultaneously by selecting superior families based on these traits. On the other hand, the shape of the logs might be improved by effective silvicultural treatments. Based on the PCA and cluster analysis, 18 families were classified into three groups: Group A, non-structural solid wood; Group B, candidates for next-generation and solid wood for structural purposes; and Group C, for production purposes requiring high wood yields. The obtained results in the present study can contribute to the increase in *N. macrophylla* wood volume with desirable properties for the wood industry.

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REFERENCES

- Akaike H. 1998. Information theory and an extension of the maximum likelihood principle. In: Parzen E, Tanabe K, Kitagawa G, editors. Selected papers of Hirotugu Akaike. Springer series in statistics. New York: Springer; p. 199–213.
- Bates DM. 2022. lme4: Mixed-effects modelling with R. <https://people.math.ethz.ch/~maechler/MEMO-pages/1MMwR.pdf> (cited February 2, 2024).
- Chung AYC, Pereira JT, Hastie A, Paul V, Johnlee EB. 2016. New records of insects associated with red laran (*Neolamarckia macrophylla*) in Sabah. *Sepilok Bulletin* 23&24: 1–14.
- Cossalter C and Pye-Smith C. 2003. *Fast-wood forestry: Myths and realities*. Center for International Forestry Research. Bogor.
- Donaldson L. 2008. Microfibril angle: measurement, variation, and relationships – A review. *LAWA Journal* 29: 345–386.
- Erwinsyah, Harianto, Sinaga BM, Simangunsong BCH. 2017. Analisis penawaran dan permintaan kayu bulat untuk pemenuhan kebutuhan industri kayu lapis, kayu gergaji dan pulp di Indonesia [Analysis of supply and demand of logs for plywood, sawn timber and pulp industries in Indonesia]. *Sosio-E-Kons* 9: 117–124.
- Falconer DS, Mackay TFC. 1989. *An introduction to quantitative genetics 3rd edition*. Longman Scientific and Technical. Essex.
- Halawane JE, Hidayah HN, Kinho J. 2011. *Prospek pengembangan jabon merah (Anthocephalus macrophyllus (Roxb.) Havil), solusi kebutuhan kayu masa depan [Jabon merah (Anthocephalus macrophyllus (Roxb.) Havil) development prospects, solutions to future challenges]*. Research and Development Institute for Environment and Forestry Manado. North Sulawesi.
- Hidayati F, Sunarti S, Setyaji T, Nirsatmanto A. 2020. Physical and mechanical properties of jabon merah (*Anthocephalus macrophyllus*) planted in Wonogiri, Central Java. *Journal of Tropical Forests* 8: 357–365.
- Ihda FV, Lukmandaru G, Nirstamanto A. 2023. Extractive content of white jabon (*Neolamarckia cadamba*) and red jabon (*Neolamarckia macrophyllus*) stemwood from Wonogiri, Central Java. *Jurnal Ilmu Kehutanan* 17: 67–75.
- Irawan US, Purwanto E. 2014. White jabon (*Anthocephalus cadamba*) and red jabon (*Anthocephalus macrophyllus*) for community land rehabilitation: improving local propagation efforts. *Agricultural Science* 2: 36–45.
- Ishiguri F, Aiso H, Aruga K, Ohshima J, Iizuka K, Yokota S. 2021. Stress-wave velocity of stems, dynamic Young's modulus of logs, and wood properties in two broad-leaved tree species. *Bulletin of the Utsunomiya University Forests* 57: 15–21.
- Ishiguri F, Diloksumpun S, Tanabe J, Iizuka K, Yokota S. 2013. Stress-wave velocity of trees and dynamic Young's modulus of logs of 4-year-old *Eucalyptus camaldulensis* trees selected for pulpwood production in Thailand. *Journal of Wood Science* 59: 506–511.
- Ishiguri F, Matsui R, Iizuka K, Yokota S, Yoshizawa N. 2008. Prediction of the mechanical properties of lumber by stress-wave velocity and Pylodin penetration of 36-year-old Japanese larch trees. *Holz als Roh-und Werkstoff* 66: 275–280.
- Livestock, Fisheries, and Forestry Statistics. 2023. *Statistics of forestry production 2022*. Statistics Indonesia. Jakarta.
- Masendra, Nezu I, Ishiguri F, Hidayati F, Nirsatmanto A, Sunarti S, Surip, Kartikaningtyas D, Takashima Y, Takahashi Y, Ohshima J, Yokota S. 2023. Variations of growth and wood traits in standing trees of the third-generation *Acacia mangium* families in Indonesia. *Silvae Genetica* 72: 150–162.
- Nezu I, Ishiguri F, Aiso H, Diloksumpun S, Ohshima J, Yokota S. 2023. Evaluation of xylem maturation manner for solid wood production from *Eucalyptus camaldulensis* planted in Thailand. *Tropics* 32: 49–63.
- Ngadianto A, Ishiguri F, Nezu I, Takahashi Y, Tanabe J, Hidayati F, Irawati D, Ohshima J, Yokota S. 2020. Wood properties and simulated modulus of elasticity of glulam in three fast-growing tree species grown in community forests in Yogyakarta, Java Island, Indonesia. *Tropics* 29: 89–104.
- Pertiwi YAB, Aiso H, Ishiguri F, Wedatama S, Marsoem SN, Ohshima J, Iizuka K, Yokota S. 2017. Effect of radial growth rate on wood properties of *Neolamarckia cadamba*. *Journal of Tropical Forest Science* 29: 30–36.
- Punches J. 2004. *Tree growth, forest management, and their implications for wood quality*. Pacific Northwest Extension Publication (PNW 576). Oregon State University.
- R Core Team. 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.r-project.org/> (cited November 2, 2023).
- Salas-Eljatib C, Mehtätalo L, Gregoire TG, Soto DP, Vargas-Gaete R. 2021. Growth equations in forest research: Mathematical basis and model similarities. *Current Forestry Report* 7: 230–244.
- Sandalayuk D, Masrukhin, Djabar M, Ruruh A, Ernikaewati. 2023. Thinning on the growth of jabon merah trees (*Anthocephalus macrophyllus*) in the industrial plantation forest area. *Journal of Research in Science Education* 9: 5852–5858.
- Saranpää P. 2003. Wood density and growth. In: Barnett J and Jeronimidis G (eds) *Wood quality and its biological basis*. Blackwell Publishing, Oxford. 87–113.
- Setyaji T, Sunarti S, Nirsatmanto A, Kartikaningtyas D, Yuliastuti DS. 2012. *General information of seed source (F–1) of Anthocephalus cadamba and Anthocephalus macrophyllus establishment in Wonogiri, Central Java Fiscal Year 2010–2012*. FTIP-P3-No.60. Forest Research and Development Agency. Ministry of Forestry Indonesia.
- Sobue N. 1986. Measurement of Young's modulus by the transient longitudinal vibration of wooden beams using a fast Fourier transformation spectrum analyzer. *Mokuzai Gakkaishi* 32: 744–747.
- Statistics of Wonogiri Regency. 2023. <https://wonogirikab.bps.go.id/indicator/151/164/1/curah-dan-hari-hujan.html> (cited December 7, 2023).
- Surip, Indrioko S, Nirsatmanto A, Setyaji T. 2017. Effect of selection on genetic gain of first-generation seedling seed orchards of jabon merah (*Anthocephalus macrophyllus* (Roxb.) Havil) established in Wonogiri. *Jurnal Pemuliaan Tanaman Hutan* 11: 33–44.