EFFECT OF RADIAL GROWTH RATE ON WOOD PROPERTIES OF *NEOLAMARCKIA CADAMBA*

YAB Pertiwi[1, 2, 3], H Aiso[1, 2], F Ishiguri[1, *], S Wedatama[3], SN Marsoem[3], J Ohshima[1], K Iizuka[1] & S Yokota[1]

[1]*Faculty of Agriculture, Utsunomiya University, Utsunomiya, 321-8505, Japan*
[2]*United Graduate School of Agricultural Science, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan*
[3]*Faculty of Forestry, Gadjah Mada University, Yogyakarta, 55281, Indonesia*

**ishiguri@cc.utsunomiya-u.ac.jp*

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The effect of radial growth rate on anatomical characteristics and wood properties were examined in 4-year-old *Neolamarckia cadamba*. A total of 63 standing trees were categorised into three groups (slow, middle and fast growth) according to their stem diameter. Mean values of stem diameter, tree height and stress-wave velocity were 15.0 cm, 13.4 m and 2.99 km s^{-1} respectively. No significant correlations were found between growth characteristics and stress-wave velocity of stems. In addition, dynamic Young's modulus of the logs differed between trees with common radial growth rate. Mean values of fibre length, diameter and wall thickness, and vessel element length, diameter and frequency were 1.52 mm, 26.9 and 1.8 µm, and 0.72 mm, 156 µm and 7.4 vessels mm^{-2} respectively. Mean values of basic density and compressive strength were 0.30 g cm^{-3} and 15.5 MPa respectively. No significant differences in almost all anatomical characteristics and wood properties were recognised between the three categories, suggesting that these characteristics were independent of radial growth rate.

Keywords: Stress-wave velocity, vessel morphology, fibre morphology, basic density, compressive strength

INTRODUCTION

In tropical regions, establishment of plantation of fast-growing tree species is considered as a profitable investment (Cossalter & Pye-Smith 2003). In Indonesia, *Falcataria moluccana* (syn. *Paraserianthes falcataria*) is the most important fast-growing tree species for the establishment of large-scale industrial plantations as well as small-scale plantations known as community forests, particularly on Java Island. However, this situation has changed due to the massive outbreaks of diseases throughout Java Island. In 2003, *F. moluccana* plantations on Java Island were attacked by gull rust disease (Baskorowati et al. 2012). After the spread of the disease throughout island, wood production using *F. moluccana* has declined. However, demand for wood continues to increase in Indonesia, resulting in plantation industries and communities actively looking to identify alternative fast-growing tree species.

Neolamarckia cadamba (jabon is the local name in Indonesia, syn. *Anthocephalus cadamba*), has been identified as an important alternative fast-growing tree species for exploitation by industries and communities in Indonesia. *Neolamarckia cadamba* is native to south and south-east Asian countries (Soerianegara & Lemmens 1994). It is light weight hardwood with straight grain and white with yellow tinge darkening to creamy yellow. The timber of this species is used for plywood, pulp and paper, packing cases and inexpensive furniture (Soerianegara & Lemmens 1994). To date, reports on serious pests and diseases for *N. cadamba* plantations are scarce.

Fast-growing tree species are typically selected to establish plantations due to expectation of high growth rate and profit. However, some customers believe that wood obtained from fast-growing tree species with high growth rate may be of inferior quality compared with that from slower-growing tree species. In addition, wood harvested at younger age contains high percentage of wood with unstable quality, similar to juvenile wood in softwood. Studies on xylem maturation have been conducted in several fast-growing tree species in Indonesia so as to reduce the percentage of unstable-quality wood and to improve wood quality similar to that of mature wood in softwood (Kojima et al. 2009, Makino et al. 2012). In *Acacia* spp. and *Falcataria* spp., xylem maturation depends on diameter growth, whereas in *Eucalyptus* spp., it is controlled by cambium age (Kojima et al. 2009). In *N. cadamba*, reports on wood maturation based on fibre length and microfibril angle measurements have been reported by several researchers (Darmawan et al. 2013, Fajriani et al. 2013). However, there is not much research done on the anatomical characteristics and wood properties of the species.

The objective of the current study was to investigate the effect of radial growth rate on anatomical characteristics and wood properties of *N. cadamba*. Growth characteristics and stress-wave velocity were examined for the stems of 4-year-old *N. cadamba* trees planted in a community forest in East Java, Indonesia. The dynamic Young's modulus was additionally investigated in logs of three trees from the middle-growth category.

MATERIALS AND METHODS

Field experiments

The 4-year-old *N. cadamba* trees used in the present study were planted in a community forest in Krucil, Probolinggo, East Java, Indonesia (113° 28' E, 7° 53' S, 830 m in altitude). Stem diameter, tree height and stress-wave velocity of stems were measured for 63 standing trees. Stem diameter was measured at 1.3 m above the ground using diameter tape. Tree height and stress-wave velocity were measured using height meter and commercial handheld stress-wave timer respectively (Ishiguri et al. 2007, 2011, 2012, Istikowati et al. 2014). To evaluate the effects of radial growth rate on wood properties, the trees were categorised into three groups based on the mean and standard deviation (SD) of stem diameter: (1) slow growth (mean – SD), (2) middle growth (mean ± SD) and (3) fast-growth (mean + SD) (Ishiguri et al. 2012).

Core samples were collected from three trees in each group to measure anatomical characteristics, basic density and compressive strength. The core samples (5 mm in diameter) were obtained from the nine trees using core borer approximately 1.3 m above the ground. In addition, three trees in middle-growth group were harvested and logs of 2.6 m length were then obtained from 1.2 m above the ground towards the tree top, totalling nine logs (three logs from each tree). Dynamic Young's modulus values of the logs were determined by the tapping method (Sobue 1986).

Anatomical characteristics

Due to indistinct growth rings, anatomical characteristics were determined using 1-cm segments from the pith to the bark. Before sectioning, samples were boiled with 25% glycerin aqueous solution for 2 hours using dry block heater. Transverse sections of 15 µm in thickness were obtained by sliding microtome and the sections were stained with 1% safranin and dehydrated by graded ethanol. Dehydrated sections were dipped into xylene for 30 min, and then mounted and covered with cover slips. Images of the transverse section were recorded using a digital camera attached to a light microscope. Fibre diameter, vessel diameter and vessel frequency (number of vessels mm^{-2}) were determined by ImageJ software. Tangential and radial diameters were measured in 50 fibres and 30 vessels. Vessel frequency was determined using five digital images.

Small sections were obtained at 1-cm intervals from the pith to the bark and were macerated by Schulze's solution. Macerated samples were then washed with distilled water several times. Each sample was placed on a slide glass, mounted with 75% glycerin aqueous solution and covered with a cover slip. Fibre and vessel lengths were measured using microprojector and digital callipers. A total of 50 fibres and 30 vessels were measured in each section.

Wood properties

Due to indistinct growth rings, basic density was determined at 1-cm intervals from the pith to the bark in core samples. Basic density was calculated by dividing oven-dry weight by green volume determined by the water displacement method (Barnett & Jeronimidis 2003). Compressive strength parallel to grain was additionally measured in core samples in the green condition at 5-mm intervals from the pith to the bark using strength testing equipment for core samples according to the method of Ishiguri et al. (2012).

Discs of 8 to 10 cm in thickness were collected from different height positions (1.2, 3.8, 6.5 and 9.2 m above the ground) of the three harvested trees. Small-clear specimens (5 (R) × 20 (T) × 80 (L) mm) for the static bending test were prepared at 1-cm intervals from the pith. Before the test, specimens were conditioned in desiccators saturated with sodium chloride solution for two weeks at 20 °C to obtain constant moisture content. Static bending test was conducted using universal testing machine with a 70 mm span. Load was applied to the center of the tangential surface at a speed of 1 mm min^{-1}. The load and deflection were recorded using personal computer and the modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated.

Statistical analysis

Analysis of variance (ANOVA) was employed to detect significant differences in anatomical characteristics and wood properties between the three growth categories. ANOVA test was used to evaluate differences in dynamic Young's modulus values of the logs and static bending property of small clear specimens between the three harvested trees. Correlation coefficients were determined to ascertain the relationship between stress-wave velocity, stem diameter and tree height in standing trees. The ANOVA test and determination of correlation coefficient were conducted using Excel 2007.

RESULTS AND DISCUSSION

Growth characteristics and stress-wave velocity

Table 1 shows statistical values of stem diameter, tree height and stress-wave velocity for all standing trees at the experiment site. The numbers of trees in the slow-, middle- and fast-growth categories were 10, 45 and 8 respectively. Mean stem diameter values in the slow-, middle- and fast-growth categories were 10.3, 14.8 and 21.9 cm respectively. Tree height values in the slow-, middle- and fast-growth categories were 10.8, 13.3 and 17.2 m respectively while stress-wave velocity values were 3.01, 2.99 and 3.01 km s^{-1} respectively. Stem diameter and tree height showed significant differences at the 1% level between categories but there was no significant difference in stress-wave velocity. Mean values of stress-wave velocity were 3.08 km s^{-1} for 13-year-old *F. moluccana* trees (Ishiguri et al. 2007), 3.59 and 3.75 km s^{-1} for 5- and 7-year-old *Acacia mangium* trees (Makino et al. 2012), 3.36 km s^{-1} for *Artocarpus elasticus*, 4.21 and 3.73 km s^{-1} for *Neolitsea latifolia* and *Alphitonia excelsa* respectively (Istikowati et al. 2014) and 3.03 to 3.88 km s^{-1} for 4-year-old *Eucalyptus camaldulensis* (Ishiguri et al. 2013). Stress-wave velocity values obtained for the 4-year-old *N. cadamba* trees were similar to those obtained in previous reports.

Significant positive correlation coefficient was found between stem diameter and tree height (r = 0.802), whereas no significant correlation coefficients were found between growth characteristics and stress-wave velocity (Figure 1). It has been reported that weak or no significant correlation coefficients were found between stem diameter and stress-wave velocity for some tropical hardwood species (Ishiguri et al. 2007, 2011, Makino et al. 2012, Istikowati et al. 2014). Weak negative correlation was found in *F. moluccana* (Ishiguri et al. 2007). No significant correlations were found between stem diameter and stress-wave velocity in *A. elasticus*, *N. latifolia* and *A. excelsa* (Istikowati et al. 2014). Hence, in *N. cadamba*, radial and longitudinal growth may not affect stress-wave velocity of the stem.

Table 1 Stem diameter, tree height and stress-wave velocity of *Neolamarckia cadamba* standing trees

Category	n	Stem diameter (cm)		Tree height (m)		Stress-wave velocity (km s^{-1})	
		Mean	SD	Mean	SD	Mean	SD
All trees	63	15.0	3.6	13.4	2.3	2.99	0.16
Slow-growth	10	10.3	0.9	10.8	1.1	3.01	0.15
Middle-growth	45	14.8	1.7	13.3	1.6	2.99	0.16
Fast-growth	8	21.9	3.0	17.2	2.2	3.01	0.25
Significance between categories		**		**		ns	

n = number of sample trees; SD = standard deviation, ** = significant at 1% level, ns = no significance

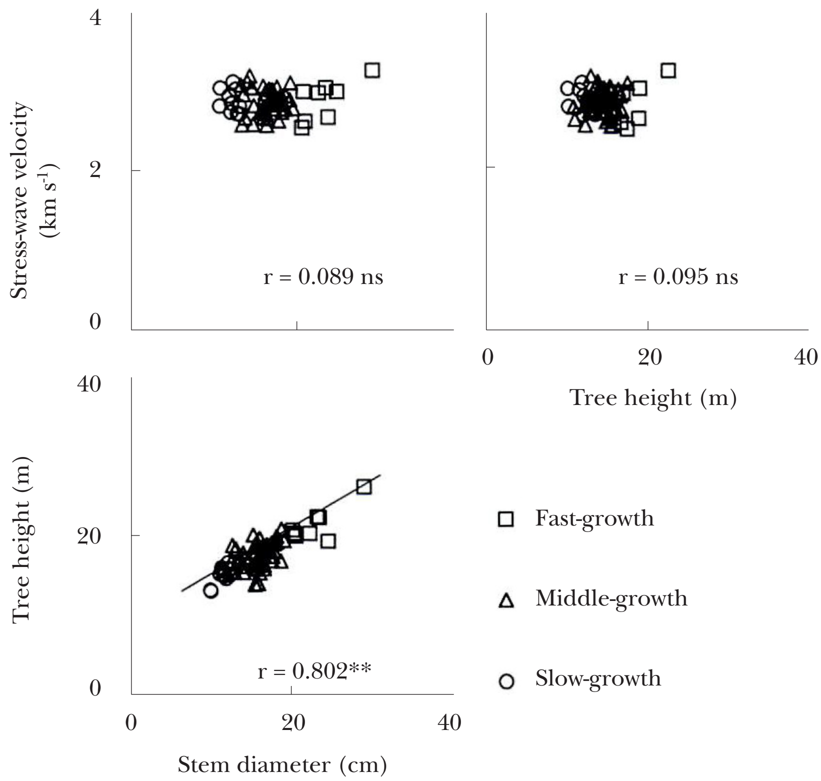

Figure 1 Relationship between growth characteristics and stress-wave velocity of stems in all standing trees; r = correlation coefficient, ** = significant at 1% level, ns = no significance; number of trees = 63

Properties of logs

The dynamic Young's modulus values of logs obtained from three different height positions of three trees in the middle-growth category ranged from 5.85 to 7.05 GPa (Table 2). In other fast-growing tree species, mean values of dynamic Young's modulus ranged from 5.62 to 8.72 GPa for logs of 13-year-old *F. moluccana* trees (Ishiguri et al. 2007) and from 10.43 to 14.52 GPa for 4-year-old *E. camaldulensis* trees (Ishiguri et al. 2013). The mean value of dynamic Young's modulus in *N. cadamba* was approximately the same as that in *F. moluccana*, whereas a relatively lower value was obtained for *E. camaldulensis.* In the present study, mean value of dynamic Young's modulus slightly increased from the base to the top of the log (Table 2). However, no significant difference in dynamic Young's modulus was found among sampling heights. In contrast, significant difference in dynamic Young's modulus was found between the three sampled trees. In the present study, the logs were obtained from the trees with approximately the same stem diameter. Therefore, dynamic Young's modulus in *N. cadamba* was variable between trees with the same radial growth rate. These results were consistent with the relationships between growth characteristics and stress-wave velocity (Figure 1). Improvement of dynamic Young's modulus in *N. cadamba* may be possible through selection of superior trees in tree breeding programmes.

Anatomical characteristics and wood properties

Mean values of fibre length, diameter and wall thickness were 1.52 mm, 26.9 µm and 1.8 µm respectively (Table 3). Mean values of vessel element length, diameter and frequency were 0.72 mm, 156 µm and 7.4 vessels mm^{-2} respectively. These values were similar or relatively smaller compared with those obtained by other studies (Soerianegara & Lemmens 1994, Ogata et al. 2008, Fajriani et al. 2013).

Mean basic density value in the nine selected trees was 0.30 g cm^{-3} (Table 3). Mean value of oven-dry density of 15-year-old *Anthocephalus chinensis* was 0.31 g cm^{-3} (Ohbayashi & Shiokura 1990). Air-dry density of *A. chinensis* ranged

Table 2 Dynamic Young's modulus (GPa) of logs from three different height positions of three harvested *Neolamarckia cadamba* trees in middle-growth category

Tree No.	D (cm)	TH (m)	Sampling height (m)			Mean of each tree	SD of each tree	Significance between trees
			1.2–3.8	3.9–6.5	6.6–9.2			
1	15.5	11.6	5.85	5.99	6.19	6.01	0.17	
2	15.3	12.6	6.72	6.96	6.61	6.76	0.18	**
3	15.5	13.3	7.05	6.98	7.03	7.02	0.03	
Mean of each height			6.54	6.64	6.61			
SD of each height			0.62	0.57	0.42			
Significance among height				ns				

D = stem diameter, TH = tree height, SD = standard deviation, ** = significant at 1% level, ns = no significance

Table 3 Anatomical characteristics and wood properties of nine selected *Neolamarckia cadamba* trees based on their growth rate

Property	Total (n = 9)		Slow-growth (n = 3)		Middle-growth (n = 3)		Fast-growing (n = 3)		Significance among categories
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Fibre length (mm)	1.52	0.21	1.48	0.18	1.51	0.26	1.54	0.19	ns
Fibre diameter (μm)	26.9	1.8	27.0	1.8	26.4	1.6	27.2	1.8	ns
Fibre wall thickness (μm)	1.8	0.3	1.8	0.3	1.6	0.1	1.8	0.3	*
Vessel element length (mm)	0.72	0.10	0.70	0.10	0.73	0.14	0.72	0.08	ns
Vessel diameter (μm)	156	26	134	16	147	24	170	22	**
Vessel frequency (mm^{-2})	7.4	3.0	8.1	2.8	8.3	2.7	6.5	3.1	ns
Basic density (g cm^{-3})	0.30	0.06	0.29	0.04	0.32	0.05	0.30	0.06	ns
Compressive strength (MPa)	15.5	3.4	15.3	2.2	15.0	3.6	16.0	3.8	ns

n = number of trees, SD = standard deviation, ** = significant at 1% level, * = significant at 5% level, ns = no significance

from 0.29 to 0.56 g cm^{-3} (Ogata et al. 2008). The results obtained in the present study were similar to Ohbayashi and Shiokura (1990) and Ogata et al. (2008). Mean basic density values for *F. moluccana*, 5-year-old *A. mangium* and *Gmelina arborea* were 0.32 (Ishiguri et al. 2007), 0.42 (Makino et al. 2012) and 0.41 g cm^{-3} (Chowdhury et al. 2013) respectively.

Mean basic density value in the present study was similar to that of *F. moluccana* (Ishiguri et al. 2007), but was relatively lower compared with *A. mangium* and *G. arborea* (Makino et al. 2012, Chowdhury et al. 2013). Compressive strength value was 15.5 MPa at green condition for the nine selected trees (Table 3). Mean compressive strength at the green condition was 30.0 MPa for 5-year-old *A. mangium* (Makino et al. 2012). Compressive strength in *N. cadamba* was lower compared with *A. mangium*. In general, wood density positively correlates with mechanical properties (Kollman & Côté 1984). The variability of compressive strength between species is, therefore, related to the difference of wood density.

Mean values of MOE and MOR in all specimens were 5.94 GPa and 67.9 MPa respectively (Table 4). These values were similar to those reported by Darmawan et al. (2013) who reported that in 7-year-old *N. cadamba*, MOE in the pith and the bark sides were approximately 4.41 and 7.35 GPa while MOR were 34.3 and and 63.7 MPa respectively. Significant differences in MOE and MOR between the three trees were observed at the 1% level (Table 4). Static bending properties in *N. cadamba* were different between trees with a common radial growth rate. Data obtained from the static bending test explained log properties (dynamic Young's modulus) which showed

Table 4 Static bending properties of three harvested *Neolamarckia cadamba* trees in the middle-growth category

Tree	n	MC (%)		MOE (GPa)		MOR (MPa)	
		Mean	SD	Mean	SD	Mean	SD
All specimens	90	10.6	0.5	5.94	1.14	67.9	14.8
1	21	10.7	0.5	4.77	0.52	49.8	6.5
2	31	10.4	0.5	6.38	0.63	73.7	8.5
3	38	10.7	0.4	6.22	1.29	73.2	14.1
Significance among trees		ns		**		**	

n = small clear specimen number, MC = moisture content at static bending test, MOE = modulus of elasticity, MOR = modulus of rupture; SD = standard deviation, ** = significant at 1% level, ns = no significance

significant difference between the trees (Table 2). These results were also consistent with the relationship between growth characteristics and stress-wave velocity (Figure 1) in which stress-wave velocity was independent from radial growth rate. Based on the results, improvement of mechanical properties of this species may be possible through the selection of superior trees in tree breeding programmes.

Effects of radial growth rate on anatomical characteristics and wood properties

No significant differences between categories were observed for all measured characteristics, except for fibre wall thickness and vessel diameter (Table 3). Fibre wall thickness was almost the same for the slow- and fast-growth categories, whereas the lowest value was for the middle-growth category (Table 3). Vessel diameter was 134, 147 and 170 μm for slow-, middle- and fast-growth categories respectively, indicating that vessel diameter increased with increased radial growth rate. Based on the results, with some exceptions, almost all anatomical and wood properties in *N. cadamba* might be independent from radial growth rate. These results were similar to the relationship between stem diameter and stress-wave velocity of the stem (Figure 1).

CONCLUSIONS

In the present study, growth characteristics, anatomical characteristics and wood properties were investigated for 4-year-old *N. cadamba* trees. No significant correlations were found between growth characteristics (diameter and tree height) and stress-wave velocity, suggesting that growth characteristics did not affect stress-wave velocity of the stem. Dynamic Young's modulus values for logs in the middle-growth group slightly increased from the base to the top of the log. However, no significant difference in dynamic Young's modulus was found between tree heights. Dynamic Young's modulus in *N. cadamba* differed between trees with common radial growth rate, suggesting that improvement of dynamic Young's modulus was possible through selection of superior trees in tree breeding programmes. No significant differences were found in fibre length and diameter, vessel element length and frequency, basic density and compressive strength between tree-growth categories, indicating that these characteristics and properties were independent from radial growth rate. It was concluded that *N. cadamba* tree with faster growing characteristics did not always have lower quality of woods.

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