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NOTE

# 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

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**Abstract** *Eucalyptus camaldulensis* Dehnh. is extensively planted in Thailand to produce wood chips used as raw material for pulp and paper. To promote the utilization of the wood from plantation-grown *E. camaldulensis* for solid lumber, stress-wave velocity of trees and dynamic Young's modulus of logs were investigated for 4-year-old trees of eight half-sib families selected for pulpwood production on the basis of the growth characteristics in the previous tree breeding program. For the eight families, the mean stem diameter at 1.3 m above ground level and mean tree height were 7.6 cm and 11.9 m, respectively. The mean stress-wave velocity of eight families was 3.45 km/s. Dynamic Young's modulus of logs ranged from 7.88 to 17.64 GPa, and the mean value for the eight families was 11.72 GPa. Stress-wave velocity of trees was significantly correlated with dynamic Young's modulus of logs, suggesting that dynamic Young's modulus of wood can be evaluated nondestructively by stress-wave velocity of trees. Significant differences in stress-wave velocity and dynamic Young's modulus of logs were obtained among families. Thus, to promote the utilization of *E. camaldulensis* wood for solid lumber production, selection of trees with high Young's modulus should be applied to trees already selected for the growth characteristics in the previous tree breeding program.

**Keywords** *Eucalyptus camaldulensis* · Dynamic Young's modulus · Solid wood property · Tree breeding

## Introduction

*Eucalyptus camaldulensis* Dehnh. is originally distributed in Australia [1]. Because the species is fast growing, it has been used as a commercial plantation species to produce wood chips used as raw material for pulp and paper [2]. In Thailand, *E. camaldulensis* has been extensively planted for pulpwood production [3]. The rotation age of this species for pulp chip production is approximately 4–5 years. To increase the efficiency of wood production, several tree breeding programs have targeted this species [4–6]. However, wood chips from fast-growing species do not always command a high price. Therefore, the possibility of solid lumber production should be considered for plantation-grown *E. camaldulensis* trees. However, only a few reports are available for the variation of wood quality in *E. camaldulensis* [7–10].

In the previous report [10], we examined solid wood properties such as stress-wave velocity of trees, dynamic Young's modulus of logs, basic density, shrinkage, and interlocked grain in two commercial clones selected for pulpwood production in Thailand to evaluate the possibility for lumber production from plantation-grown *E. camaldulensis* trees. We found the difference in wood

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properties between the two clones. Wood properties, therefore, should be investigated for *E. camaldulensis* trees selected for the growth characteristics to promote the utilization of wood from plantation-grown *E. camaldulensis*.

In the present study, to promote the utilization of wood from plantation-grown *E. camaldulensis* trees, stress-wave velocity of trees and dynamic Young's modulus of logs were investigated for eight half-sib families of this species selected for pulpwood production on the basis of the growth characteristics. In addition, the relationships between growth characteristics and stress-wave velocity and dynamic Young's modulus were discussed.

## Materials and methods

The experimental site was located in Wang Nam Khieo, Nakhon Ratchasima, Thailand (14°29′52″N, 101°56′16″E). This progeny test stand of *E. camaldulensis* was established in 2006 using 120 half-sib families selected for the growth characteristics (Table 1) with 1.5 by 3 m spacing. Of 120 half-sib families, 10 showed superior growth and physiological characteristics [11]. In the present study, a total of 35 trees from eight families were selected from 10 families with superior growth and physiological characteristics, because the number of trees in the progeny test site was limited for two families. These 35 trees were randomly selected from the progeny test site. The experiments were done at 2010. Before this experiment, no thinning treatment was conducted. In each family, stem diameter at 1.3 m above ground level and tree height were measured for 35 trees.

Stress-wave velocity of trees was determined using the method described in the previous reports [12–14]. Stress-wave propagation time was measured from 0.5 to 1.5 m above ground level using a commercial handheld stress-wave timer (Fakopp Enterprise). Stress-wave velocity was calculated by dividing the distance between sensors (1.0 m) by the stress-wave propagation time.

Thirty-five trees from eight families were cut down after measuring their stress-wave velocity. Logs were harvested from 1.3 to 3.3 m (the first log) and from 3.3 to 5.3 m (the

**Table 1** Region and provenance of *E. camaldulensis* used in the second-generation progeny test [11]

| Region | Provenance | Family |
|---|---|---|
| Petford Region, QLD | Eccles creek/tributaries | 1, 7, 11, 12, 13, 15, 16, 17, 18, 19, 22, 23, 24, 25, 26 |
| | Eureka creek/tributaries Mishap creek | <u>33</u>, 35, 50, 51, 52, 54, 56, 57, 58, <u>60*</u>, 61, 62, 112 |
| | Mishap creek | 39, 44, 47 |
| | Hales siding | 64, 65, 67, 68, 69 |
| | Petford bridge | <u>71*</u>, 72, 144 |
| | Emuford | 76, 79, 80, 81, 99 |
| | Montalbion | 84, 85, 87, 88, 94, 96 |
| | Headwaters-emu creek | 104, 106, 107 |
| | Headwaters-emureka creek | 109 |
| | Walsh river-W. emu creek junction | 114, 115, 119, 126, 127 |
| | Flat rock pool | 129, 130, 135, 137, 139 |
| Walsh-Mitchell River, QLD | Petford bridge | 145, 149, 150, 154, 155, 156, 158 |
| | Walsh river rockwood | 162, <u>163*</u> |
| | Mt. Mulgrave | 164, 166, 170 |
| | Palmeryville | 172, 174, 176, 177, 178, 179, 180, 181 |
| | Lynd junction | 182, 183, 184, 186 |
| | Healeys yard | 187, 188, 191, 192, 193, 196, 198, 199, 201, 203 |
| Northern Territor, Western Australia, and other QLD | Katherine | <u>208*</u> |
| | Lannard river | <u>209</u> |
| | Kennedy river | 211, 217, 218, <u>219*</u> |
| | Morehead river | 224, 225, 226, <u>227*</u>, 228, 229 |
| Thailand | Thai selection | 232, 234, <u>236*</u>, 244, 246 |
| | Thailand race (control) | 991, 992, 995, <u>996*</u>, 997 |

Family numbers with *underline* were selected for the study of physiological characteristics. Families indicated with *asterisks* were used in the present study. Two families (33 and 209) were not used in the present study, because number of remained trees was limited second log) from the base. Dynamic Young's modulus of logs with bark was determined using the tapping method described in the previous reports [12, 13]. Briefly, one end of a log was hit with a small hammer to create a vibration that was then analyzed with a handheld FFT analyzer (AD3527; A&D) equipped with an accelerometer (PV-85, Rion) to obtain the first resonance frequency. Dynamic Young's modulus (*E*fr) of logs with bark was calculated from the following formula:

$$E\text{fr}(\text{GPa}) = (2lf)^2\rho \times 10^{-3}$$

where $l$ is the length of log (m), $f$ is the resonance frequency (kHz), and $\rho$ is the green density at testing (kg/m$^3$).

## Results and discussion

Table 2 shows the growth characteristics and stress-wave velocity of trees. The mean, minimum, and maximum stem diameter of 35 trees were 7.6, 5.0, and 11.5 cm, respectively. The mean values were divided into two groups according to the Tukey HSD test (5 % level). The highest mean value among families was obtained in family 60 (9.3 cm), which also showed the highest tree height (13.3 m). No significant difference in tree height was observed among families.

The stress-wave velocity of 35 trees ranged from 2.76 to 4.35 km/s (Table 2). The mean value of eight families was 3.45 km/s. The highest mean value was obtained in family 236 (3.88 km/s). In the previous study [10], stress-wave velocity of stem in 4-year-old *E. camaldulensis* ranged from 3.1 to 3.4 km/s. Blackburn et al. [15] reported that stress-wave velocity of stem in 13-year-old *E. nitens* trees were 3.36, 3.23, and 3.18 for Southern, Northern, and Connor's Plain races, respectively. The obtained values in the present study for 4-year-old *E. camaldulensis* trees are similar to those obtained by Blackburn et al. [15] and Ishiguri et al. [10].

Makino et al. [16] reported that no significant correlation was found between stem diameter and stress-wave velocity in 5- and 7-year-old trees of *Acacia mangium*, a tropical fast-growing plantation species. Non-significant or weak negative correlations were also found in other tropical hardwood species, such as *Paraserianthes falcataria* [12] and *Pericopsis mooniana* [14]. As shown in Fig. 1a, significant positive correlation was found between stem diameter and stress-wave velocity, suggesting that characteristics of fast growth in radial direction in young trees of *E. camaldulensis* might result in increase of stress-wave velocity of wood. Kojima et al. [17] reported that boundary diameters between juvenile wood zone, transition zone from juvenile wood to mature wood, and mature wood zone were determined by radial variation of wood fiber length. They reported that average boundary diameters of juvenile wood zone and transition zone in 11-year-old *E. globulus* and 14-year-old *E. grandis* were 21.31 and 21.06 cm, respectively. Thus, almost all stems of 4-year-old *E. camaldulensis* used in the present study contained xylem with unstable wood properties, such as juvenile wood. Significant positive correlations between diameter and stress-wave velocity found in the present study might be related to existence of xylem with unstable wood properties in stem. However, further research is needed for clarifying the reasons for increase of stress-wave velocity with increase in the radial growth rate. On the other hand, significant positive correlation was also found between stem diameter and tree height (Fig. 1b). This is also true for the *P. mooniana* [14].

Dynamic Young's modulus of logs ranged from 7.88 to 17.64 GPa (Table 3), with family 219 showing the highest mean value in both the first (13.56 GPa) and the second (15.47 GPa) logs. In *E. camaldulensis*, the modulus of

**Table 2** Stem diameter, tree height, and stress-wave velocity of trees in eight half-sib families

| Family | *n* | Stem diameter (cm) | | | | Tree height (*m*) | | | | Stress-wave velocity (km/s) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Min | Max | Mean | SD | Min | Max | Mean | SD | Min | Max |
| 60 | 4 | 9.3a | 1.6 | 7.8 | 11.5 | 13.3a | 1.1 | 11.8 | 14.5 | 3.48ab | 0.40 | 3.24 | 4.07 |
| 71 | 4 | 7.7 ab | 0.9 | 6.8 | 8.5 | 11.3a | 1.2 | 9.6 | 12.4 | 3.03b | 0.27 | 2.76 | 3.31 |
| 163 | 4 | 6.7ab | 1.0 | 5.9 | 8.0 | 11.2a | 1.2 | 9.6 | 12.2 | 3.34ab | 0.24 | 3.09 | 3.63 |
| 208 | 5 | 6.5b | 0.7 | 5.8 | 7.5 | 10.3a | 0.7 | 9.6 | 11.2 | 3.15b | 0.25 | 2.79 | 3.43 |
| 219 | 5 | 8.2ab | 1.1 | 7.0 | 10.0 | 13.0a | 1.1 | 11.2 | 14.0 | 3.77a | 0.25 | 3.49 | 4.04 |
| 227 | 5 | 8.2ab | 1.2 | 6.5 | 9.8 | 12.5a | 1.7 | 10.5 | 14.3 | 3.43ab | 0.12 | 3.27 | 3.57 |
| 236 | 4 | 8.1ab | 1.4 | 6.2 | 9.5 | 12.0a | 2.1 | 9.7 | 14.7 | 3.88a | 0.33 | 3.57 | 4.35 |
| 996 | 4 | 6.6ab | 1.7 | 5.0 | 8.5 | 11.5a | 2.2 | 9.6 | 14.3 | 3.50ab | 0.25 | 3.18 | 3.80 |
| Total | 35 | 7.6 | 1.4 | 5.0 | 11.5 | 11.9 | 1.6 | 9.6 | 14.7 | 3.45 | 0.36 | 2.76 | 4.35 |

The same alphabet letters followed by mean value indicate no significance at 5 % level according to the Tukey HSD test

*n* number of sample, *SD* standard deviation, *Min* minimum, *Max* maximum elasticity (MOE) in static bending at 12 % moisture content was reported to be 11.18 GPa [1]. In previous study [10], dynamic Young's modulus of logs of 4-year-old *E. camaldulensis* ranged from 8.0 to 10.7 GPa. Ilic [18] reported that dynamic Young's modulus of small clear specimens (moisture content = 12 %) of *E. delegatensis* was 18.0 GPa. Our results obtained in 4-year-old *E. camaldulensis* are similar to the results obtained in other *Eucalyptus* spp.

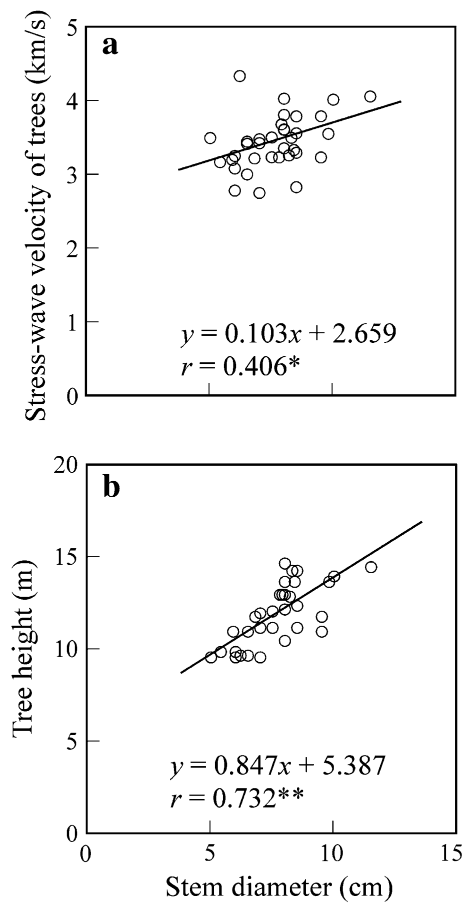


**Fig. 1** Relationships between stem diameter and tree height and stress-wave velocity of *E. camaldulensis* trees. Sample size 35, *r* correlation coefficient. *Asterisk* significance at 5 % level, *double asterisk* significance at 1 % level

It is known that dynamic Young's modulus of logs of sugi (*Cryptomeria japonica* D. Don) varies in longitudinal directions [19, 20]. Hirakawa et al. [19] reported that the longitudinal variations in dynamic Young's modulus of logs might be related to the within-tree variation of microfibril angle. In our study, the value was higher in the second than in the first logs. In *E. delegatensis*, Evans and Ilic [21] reported that microfibril angle accounted for >85 % of both Young's modulus and specific Young's modulus in longitudinal direction. Therefore, the longitudinal variation of dynamic Young's modulus of logs in *E. camaldulensis* might be also related to the within-tree variation of microfibril angle, although further research is still needed to clarify this relationship.

Figure 2 shows the relationships between stem diameter and dynamic Young's modulus of logs. Dynamic Young's modulus has been reported to be independent of growth characteristics [22, 23]. In the present study, no significant correlations were found between stem diameter and dynamic Young's modulus of the first or second logs, which is in accordance with these reports.

Stress-wave velocity of trees has been reported to be positively correlated with dynamic Young's modulus of logs [13, 23–26]. Iki et al. [26] reported that a significant correlation ($r = 0.723$) was found between stress-wave velocity of trees and dynamic Young's modulus of logs in 47 clones of the plus trees in todomatsu (*Abies sachalinensis*). In the present study, a significant positive correlation ($r = 0.644$, 1 % level) was found between stress-wave velocity of stem and dynamic Young's modulus (Fig. 3).

**Table 3** Dynamic Young's modulus of logs in eight half-sib families

| Family | *n* | First log (GPa) | | | | Second log (GPa) | | | | Mean (GPa) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Min | Max | Mean | SD | Min | Max | Mean | SD | Min | Max |
| 60 | 4 | 10.30ab | 1.20 | 9.27 | 11.91 | 11.96ab | 1.65 | 10.76 | 14.28 | 11.13ab | 1.33 | 10.14 | 13.09 |
| 71 | 4 | 9.73b | 1.72 | 7.88 | 11.56 | 11.12b | 2.89 | 8.00 | 14.99 | 10.43b | 2.25 | 7.94 | 13.28 |
| 163 | 4 | 10.99ab | 1.07 | 9.85 | 12.34 | 12.62ab | 1.21 | 11.09 | 14.03 | 11.80ab | 0.90 | 10.47 | 12.43 |
| 208 | 5 | 10.13b | 1.14 | 8.20 | 11.22 | 11.47b | 1.34 | 9.68 | 13.25 | 10.80b | 1.21 | 8.94 | 12.23 |
| 219 | 5 | 13.56a | 1.80 | 10.90 | 15.94 | 15.47a | 1.89 | 13.15 | 17.64 | 14.52a | 1.71 | 12.03 | 16.26 |
| 227 | 5 | 11.22ab | 1.42 | 9.87 | 13.12 | 12.33ab | 2.05 | 9.53 | 15.04 | 11.77ab | 1.67 | 9.70 | 14.08 |
| 236 | 4 | 11.99ab | 1.59 | 10.49 | 13.75 | 12.49ab | 1.47 | 10.49 | 13.63 | 12.24ab | 1.48 | 10.49 | 13.69 |
| 996 | 4 | 10.90ab | 1.76 | 8.35 | 12.33 | 11.76ab | 1.72 | 10.02 | 14.03 | 11.33ab | 1.53 | 9.66 | 13.18 |
| Total | 35 | 11.10 | 1.81 | 7.88 | 15.94 | 12.35 | 2.17 | 8.00 | 17.64 | 11.72 | 1.89 | 7.94 | 16.26 |

The same alphabet letters followed by mean value indicate no significance at 5 % level according to the Tukey HSD test. The first and second logs were harvested from 1.3 to 3.3 m and from 3.3 to 5.3 m above ground level, respectively

*n* number of sample, *SD* standard deviation, *Min* minimum, *Max* maximum

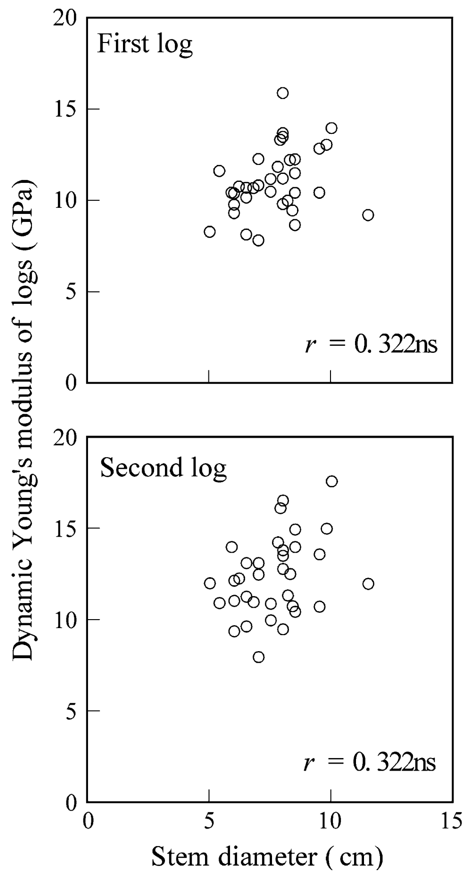


**Fig. 2** Relationships between stem diameter and dynamic Young's modulus of logs. Sample size 35, *r* correlation coefficient, *ns* no significance. The first and second logs were harvested from 1.3 to 5.3 m and from 5.3 to 7.3 m above ground level, respectively

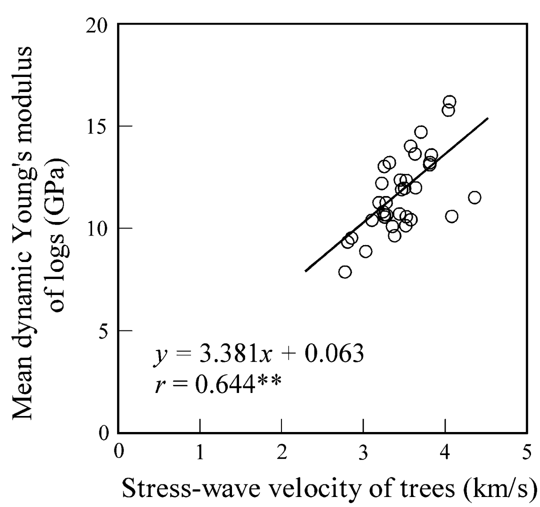


**Fig. 3** Relationship between stress-wave velocity of trees and mean dynamic Young's modulus of logs. Number of sample 35, *r* correlation coefficient. *Double asterisk* significance at 1 % level. Mean dynamic Young's modulus of logs was calculated by averaging the values for the first and second logs from each tree

These results suggest that stress-wave velocity of stem is a powerful tool for selecting trees with high mechanical properties for tree breeding programs of *E. camaldulensis*.

## Conclusion

In the present study, stress-wave velocity of stem and dynamic Young's modulus of logs were investigated for 4-year-old *E. camaldulensis* trees from eight half-sib families selected for pulpwood production in Thailand. These half-sib families had also superior growth and physiological characteristics. Significant positive correlation was found between stem diameter and stress-wave velocity of stem. There was no significant correlation between stem diameter and dynamic Young's modulus of logs. In addition, significant among family variations were found in stem diameter, stress-wave velocity of stem, and dynamic Young's modulus of logs, suggesting that Young's modulus may differ even in trees with superior growth and physiological characteristics. Therefore, for solid lumber production from *E. camaldulensis*, trees with high Young's modulus should be selected from the trees already selected for the growth characteristics in the previous tree breeding programs.

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