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Evaluation of standing tree quality of Japanese cedar grown with different spacing using stress-wave and ultrasonic-wave methods

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Abstract The quality of wood in 47-year-old standing trees of Japanese cedar grown in five plantation sites with different spacing (A, 1 × 1 m; B, 2 × 2 m; C, 3 × 3 m; D, 4 × 4 m; E, 5 × 5 m) was evaluated using stress-wave and ultrasonic-wave propagation methods. The magnitude of the velocities of these waves and the calculated dynamic modulus of elasticity (MOE) were used as indexes for assessing wood quality in standing trees. Results indicated that plantation spacings had moderate influence on the stress-wave and ultrasonic-wave velocities, and the degree of influence varied with the wave-propagating direction. Regardless of the testing method used, the velocities of waves propagated parallel to the grain in the standing trees with medium and poor growth conditions were significantly greater than those with superior growth conditions. The dynamic MOE of the trunk of standing trees of Japanese cedar was calculated by adjusting the effective mobility of free water and effective density in the trunk at various moisture contents. Results indicated that the dynamic MOE of wood in the standing trees of Japanese cedar was affected somewhat by the testing methods used. Furthermore, the dynamic MOE of the wood in the standing trees varied with the growth conditions imposed.

Key words Japanese cedar standing tree · Plantation spacing · Stress-wave method · Ultrasonic-wave method · Growth conditions

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Introduction

It would be beneficial for forest-based industries if information on the quality and mechanical properties of wood in standing trees can be obtained before harvesting. If the quality of wood in a standing tree can be assessed, the variation of wood quality during growth may be predictable; and perhaps an evaluation of these variations as influenced by season changes or between plantation sites and individual stands is feasible. Furthermore, a classification of stands or sites may be established. If such a database can be established, optimal timber management practices, such as pruning, thinning, and logging operations, may be developed.

In general, the quality of wood in standing trees is assessed by their annual ring width, earlywood/latewood ratio, and densities in the increment core extruded from a standing tree using the increment growth borer. In this study, the stress wave generated by an impact hammer or ultrasonic pulse was used to measure the velocities of these waves propagated through the wood to determine their dynamic modulus of elasticity. The applicability of vibration modes on wood materials for assessing their quality has been investigated extensively in recent years,[1–10] but most studies used small-dimension wood specimens,[1,9–11] with only a few studies focused on standing trees and logs.[5–7,11–13]

In a series of investigations on the wood quality of Japanese cedar (*Cryptomeria japonica* D. Don), trees grown at five plantation sites with different spacing were evaluated.[14–17] The study was conducted with hammer impact blows on standing trees grown at different plantation sites. The signal recording on the sides along the longitudinal axis of the stems for collecting the data were used to evaluate and predict the quality of the wood in standing trees. Ultrasonic pulse tests were conducted on the same sample trees, and a comparison was made between the two nondestructive tests.

Table 1. Residual trees of different age groups for five different plantation spacings

Age group (years)	Treatment (plant spacing) (trees/hectare)				
	Type A (1 × 1 m)	Type B (2 × 2 m)	Type C (3 × 3 m)	Type D (4 × 4 m)	Type E (5 × 5 m)
1	10000[a]	2500	1100	630	400
5	6180	1977	893	590	383
10	5317	1883	833	590	377
15	4580	1807	830	590	373
20	2410	1617	800	567	367
30	1807	1370	770	557	360
35	1613	1297	750	550	353
47	1174	983	653	500	302

[a]The number of tree (trees/ha) was calculated from the number of existing trees at various plantation sites (trees/0.3 ha)

Materials and methods

Japanese cedar standing trees

Conditions of experimental forest site

The experimental sites were located in the no. 173 plot, third branch station, Chi-Tou Working Station of the Experimental Forest of National Taiwan University. The area of the experimental site was 1.5 hectare (ha), which was divided into 15 small plots, each of 0.1 ha. Five spacings were used in this study, and the number of trees per hectare was selected by a random method; each type of plantation spacing had three smaller plots. The five plantation spacings were as follows: type A, 1 × 1 m (10000 trees/ha); type B, 2 × 2 m (2500 trees/ha); type C, 3 × 3 m (1110 trees/ha); Type D, 4 × 4 m (630 trees/ha); and type E, 5 × 5 m (400 trees/ha). The seedlings were 1-year-old vegetative (cuttings) Japanese cedar. Seedlings of the same size and with vigorous growth had been selected for the plantation, which was started in 1950. At the time of the experiment the planted trees were 47 years old. The experimental sites were inspected for the number of standing trees and their diameter at breast height (DBH) every 5 years. The residual trees on these five types of spacing plot are shown in Table 1. To foster the growth of residual trees, the restrained-growth trees and small-diameter trees in the type A plot was thinned in 1965, with a thinning intensity of 40%.

Sample trees

Because the stress-wave and ultrasonic-wave tests were conducted on total standing trees, the measurements required a large amount of work; in fact, it was difficult. The DBH of total standing trees at each site was measured to obtain average values and the standard deviation. From each site the DBH values of standing trees were classified into three groups, including: $(D) - 1\ (SD) <$ medium $< (D) + 1\ (SD)$; $(D) + 1\ (SD)$, superior $< (D) + 1.96\ (SD)$; and $(D) - 1.96\ (SD) <$ poor $< (D) - 11\ (SD)$. These groups were regarded as medium, superior, and poor growth conditions, respectively. D represented the average DBH, and SD represented the standard deviation for the respective sites. Three sample trees of superior, medium, and poor growth from each of those DBH classes were used.

Stress-wave measurement of sample trees

The stress-wave timer apparatus used in this study included the following parts: Hammer-Kit (moderately tuned hammer, 086C03, 12 kHz resonant frequency; PCB Inc., USA); accelerometer (WR728A and 728T; 21 and 20 kHz resonant frequency; WR Inc., USA); transient waveform capture board (BE 490, 8 channel, IM samples/s; Bakker Electronics, B.V. Netherland); signal processor; and FAMOS software (fast analysis and monitoring of signals V.3.0; IMC GMBH, Germany).

Specially made stainless steel nails were driven into the xylem of each sample tree. Their positions were about 70 cm above the ground with an angle of 90° between the nails and the trunk axis for connecting the accelerometer to detect the stress wave propagated parallel to the grain (M_L). N50 steel nails were driven into the xylem at a 30° angle with the trunk axis, 60 cm from the accelerometer (at about the DBH position, or 1.3 m from the ground) and served as the hitting position. Other specially made stainless steel nails were driven into the opposite hitting point for connecting the accelerometer to detect the stress wave propagated perpendicular to the grain (M_R). The setup for this test is shown in Fig. 1.

The stress-wave test was conducted by a hammer hitting the head of an N50 nail. The vibration waves were detected from a accelerometer interfaced with a microcomputer for storing field data to be analyzed when calculating stress-wave propagation times in the laboratory. The stress-wave velocity in sample trees was measured once every 45 days, for a total of eight times dating from July 1996 to August 1997.

The interval between initiation of the stress wave generated by the accelerometer inside the hammer and the receiving accelerometer was considered the time difference (Δt). The tests were repeated several times at the same hitting position, and the average value was considered the time difference for the stress wave for each sample tree. The

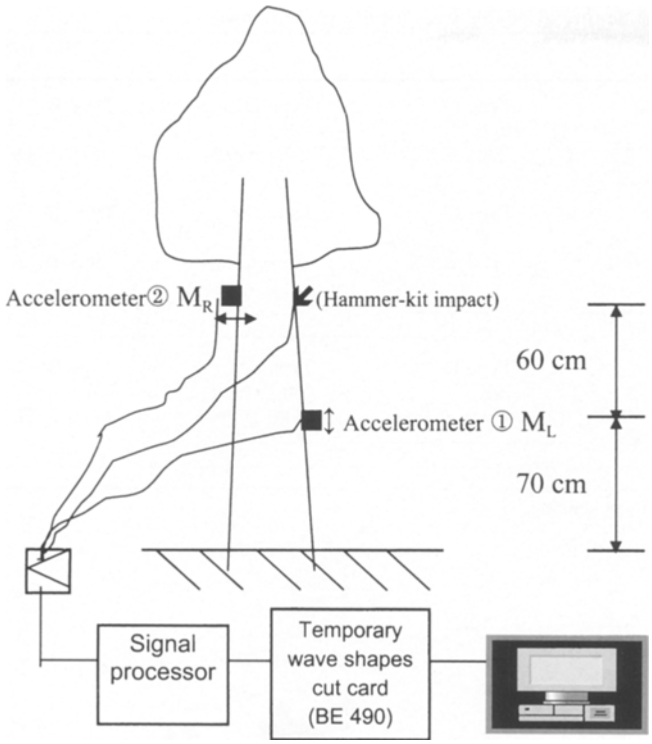

Fig. 1. Stress wave testing applied on a standing tree. Hammer kit (an accelerometer was stored inside for generating and detecting stress waves. Resonant frequency was 12 kHz

stress-wave velocity (V_{SL}, V_{SR}) and the dynamic modulus of elasticity (E_D) were calculated from the following formulas.

$$V_{SL} = L/\Delta t \quad \text{(m/s)} \tag{1}$$
$$V_{SR} = \phi/\Delta t \quad \text{(m/s)} \tag{2}$$
$$E_D = V^2 \times \rho_{eff}/g \quad (\text{kgf/cm}^2) \tag{3}$$

where V_{SL} and V_{SR} are the stress-wave velocities in the direction parallel to the grain and in the radial direction, respectively; L is the distance between the hitting position and the accelerometer; ϕ is the distance between the hammer-kit impact point and the accelerometer for each sample tree; ρ_{eff} is the effective density of wood in the sample tree; and g is the gravitational acceleration. The bulk density of sample trees (ρ) was not used to calculate the dynamic modulus of elasticity; the effective density (ρ_{eff}) suggested by Sobue[13] was used instead, by taking into account the K value, which is defined as the ratio of the weight of free water vibrating simultaneously with wood cell wall substance to the weight of total free water. The ρ_{eff} was derived by multiplying K by ρ ($\rho_{eff} = \text{K} \times \rho$). A K value of 0.6 for the stress waves and 0.7 for the ultrasonic waves, obtained by the author's previous report,[18] were used.

Ultrasonic wave tests of sample trees

The ultrasonic wave apparatus (Sylvatest, frequency 16 kHz; Swiss Products) included a transmitting transducer and receiving transducer. The tests were conducted three times from May 1997 to August 1997. The tested sample

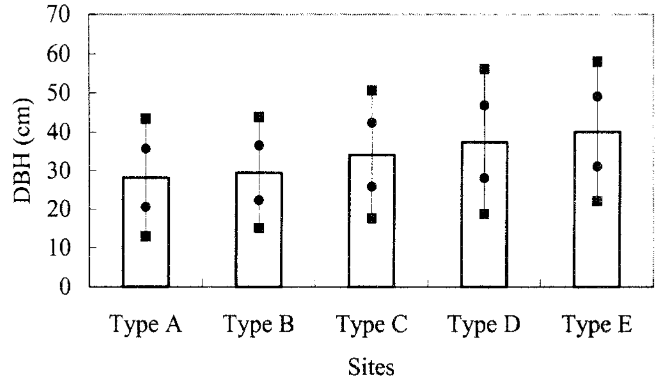

Fig. 2. Diameter at breast height (*DBH*) values of total standing trees at five plantation spacing sites. *Bars*, average DBH (*D*); *squares*, D + 1.96 (SD) and D − 1.96 (SD); *circles*, D + 1 (SD) and D − 1 (SD)

trees and the transducer positions were the same as those used for the stress-wave test. The ultrasonic wave velocities (V_{UL}, V_{UR}) were calculated using the equation

$$V_{UL} \text{ or } V_{UR} = L/T \quad \text{(m/s)} \tag{4}$$

where L is the distance between the two transducers, and T is the propagation time of the pulse from the transmitting transducer to the receiving transducer.

Measurement of moisture content and density of sample trees

When the eighth test (July 1997) was conducted, a core was obtained by a growth increment borer from the trunk of each sample tree at a site near breast height to determine the moisture content in the green condition and the bulk density. The green moisture contents of sample trees were determined using the oven-dried method.

Analyses of experimental data

The differences in stress-wave and ultrasonic-wave velocity, green moisture content, and bulk density in sample trees among five plantation spacing sites were analyzed by the multiple new-ranged Duncan's test.[19]

Results and discussion

DBH values of sample trees from five plantation sites

The DBH values for the total standing trees in five plantation sites are shown in Fig. 2. The differences in these DBH values (types A–E) were analyzed using the multiple new-ranged Duncan's test as shown in Table 2. Significant differences among types C, D, and E were observed; there was no significant difference between types A and B. Based on these results, the largest DBH values were found in type E trees followed in decreasing order by those of types D, C, B, and A.

Table 2. Results of multiple new-ranged Duncan's test for DBH and bulk density of sample trees for five plantation sites

Parameter	Data				
Plantation site	Type A	Type B	Type C	Type D	Type E
Total standing trees (no.)	352	295	197	150	91
Average DBH (cm), mean ± SD	29.0 ± 7.6	29.5 ± 7.2	34.1 ± 8.2	37.4 ± 9.3	40.0 ± 8.9
Significant difference*					
Plantation site	Type A	Type B	Type C	Type D	Type E
Medium-growth sample trees	3	3	3	3	3
Average DBH (cm), mean ± SD	26.4 ± 2.1	27.5 ± 1.0	31.2 ± 2.9	36.1 ± 1.3	36.9 ± 1.6
Significant difference*					
Plantation site	Type E	Type C	Type D	Type A	Type B
Total standing trees (no.)	352	295	197	150	91
Average bulk density (kg/m^3)	386.0 ± 56.5	397.0 ± 50.4	409.0 ± 38.6	431.0 ± 26.4	442.0 ± 57.3
Significant difference*					

Solid lines represent no significant difference between the types of plantation spacing
DBH, diameter at breast height
$*P < 0.05$

When the DBH values of the medium-growth sample trees were analyzed using the multiple new-range Duncan's test, also shown in Table 2, it was found that the average DBH for types D and E were significantly greater than those for types B and A; and that for type C was significantly greater than that for type A. Significant differences among other types were not observed. These tendencies were consistent with the results in our previous report.[14] This might be due to the fact that standing trees in type E and D sites had more growth space than those in type A and B sites.

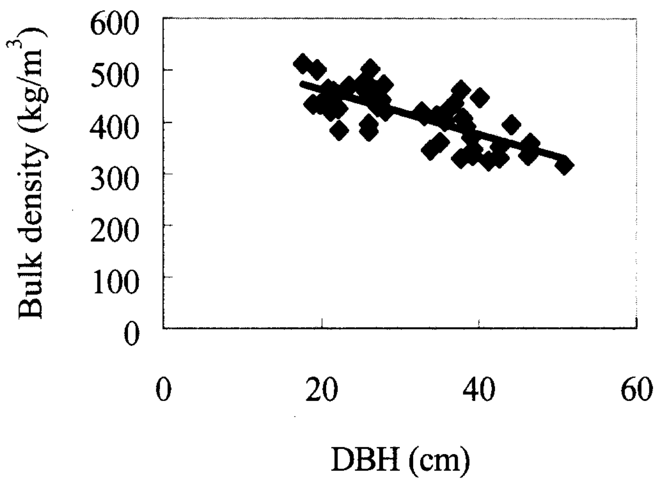

Fig. 3. Relations between DBH and bulk density

Moisture content in green condition and bulk density

Moisture content in green condition

Regardless of the growth condition of the sample trees studied, the moisture content in green wood of these sample trees was, in decreasing order, as follows: type C site (204.1%) > type E (195.7%) > type D (182.6%) > type B (176.8%) > type A (154.0%). Significant differences existed among the wood from type C and E sites and type A site. Significant differences were not observed among the wood samples obtained from the other sites. When the analysis was conducted on the basis of growth conditions, there were no significant differences in moisture content in green wood obtained from superior-, medium-, and poor-growth sample trees for the five sites.

Bulk density

Regardless of the growth conditions of the trees, the bulk density of these trees was, in decreasing order, as follows: type B 442 kg/m^3 > type A 431 kg/m^3 > type D 409 kg/m^3 > type C 397 kg/m^3 > type E site 386 kg/m^3. It was found that a significant difference existed between the wood cut from trees at the type B and E sites. There were no significant differences among the specimens cut from trees of the other sites (A, D, C), as shown in Table 2.

The relation between the DBH(D) and the bulk density of sample trees was examined. From Fig. 3 it is obvious that the bulk density values decreased linearly with increasing DBH, and the relation could be expressed by the following linear regression.

$$\text{Bulk density} = -4.32D + 549.68, \quad R^2 = 0.52 \quad F = 47.4$$

There was a significant difference ($P < 0.01$) by the F test. This suggested that in even-age stands the superior rapid-growth trees had a large DBH and wide annual rings; hence they had a lower percentage of latewood, resulting in the lower bulk densities.

This finding was similar to that in Wang and Lin's report,[16] which indicated that the highest wood density in Japanese cedar was in 1 × 1 m spaced stands, and the lowest was seen in trees from a 5 × 5 m spaced stand. This tendency

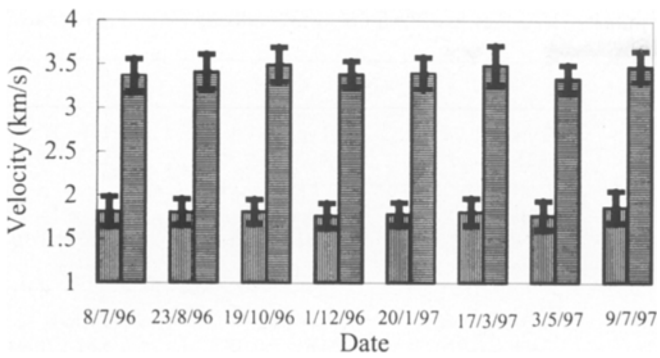

Fig. 4. Velocity of stress wave for type B standing July 1996 to July 1997. *Bars with horizontal lines*, longitudinal velocity; *bars with vertical lines*, radial velocity

may be attributed to the fact that trees grown at relatively wide spacing have shorter tracheids, the smallest percentage of latewood, and wide annual rings, as previously reported by Wang and Chen.[14]

Effects of the growing season on stress-wave velocity

The data for the stress-wave velocity propagated parallel to the grain (V_{SL}) and in the radial direction (V_{SR}) resulted from eight measurements of medium-growth trees at type B plantation sites (Fig. 4). There was a similar tendency for other types as well (A, C, D, E). When the multiple new-range Duncan's test was analyzed for the V_{SL} and V_{SR} of medium-growth trees in eight tests for each plantation spacing site (types A–E), it was found that there were no significant differences in the V_{SL} values among eight tests for each type of plantation spacing. In contrast, the V_{SR} values from the eighth test (July 8, 1997) were significantly higher than those from the fifth test (January 20, 1997), the seventh test (May 3, 1997), the fourth test (December 1, 1996), the first test (July 8, 1996), and the second test (August 23, 1996). There were no significant differences among other tests.

Although there was a significant difference in V_{SR} values by the F test, in fact the differences in V_{SR} values among the eight tests were too small to be ignored. Therefore, all the data obtained from the eight tests, including the V_{SL} and V_{SR} values, were used for the latter analyses.

At this experimental forest site the weather conditions can be divided into a rainy season (May to September) and a dry season (October to April). The first, second, seventh, and eighth tests were conducted during the rainy season, and the third to sixth tests were carried out during the dry season. The V_{SL} and V_{SR} values from these two periods were not significantly different, which might be because this experimental forest site exhibited high temperature (annual average air temperature 16.6°C) and high humidity (annual average relative humidity 91%). It was suitable for growing trees, and the variation in the wood quality of the sample trees during a growth season was minimal.

Sandoz and Lorin[12] indicated that the growth season effect on the ultrasonographic properties of standing trees is in the range of 5% variation. Lower ultrasonic wave speeds are associated with a vigorous growth season, whereas higher speeds may occur during the winter season when trees have no sap and the environmental temperature is much lower. However, environmental temperatures are not markedly reduced in Taiwan during the winter, so significant differences among the four seasons were not observed.

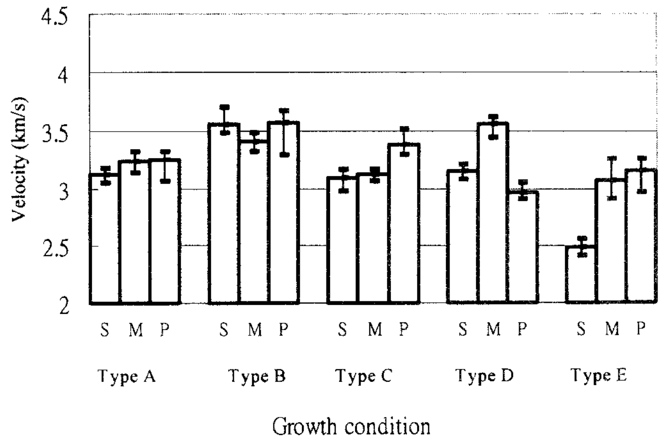

Fig. 5. Longitudinal velocity of stress waves in trees with different growth conditions at different plantation spacing sites. *Vertical lines*, maximum and minimum experimental values of three sample trees; *S*, superior-growth trees; *M*, medium-growth trees; *P*, poor-growth trees

Effects of spacing on stress-wave and ultrasonic-wave velocities

As mentioned above, because the seasonal variation is small it could be ignored. Therefore we can look at the average values collected from the eight tests of stress-wave velocity (V_{SL}, V_{UL}) and the three tests of ultrasonic wave velocity (V_{SR}, V_{UR}) for each sample tree.

The average V_{SL} and V_{SR} values for all sample trees collected from eight tests for the five sites are shown in Figs. 5, 6. Table 3 shows that the multiple new-ranged Duncan's test indicated that V_{SL} values showed significant differences (0.05 level) between types B and E and among the other three groups (C, A, D). There were no significant differences among these three groups (C, A, D). For V_{SR} values, significant differences also were not observed between types B and E and between types C and D, but significant differences existed among the other groups.

The average values for V_{UL} and V_{UR} for all sample trees collected from three tests for the five sites are shown in Figs. 7 and 8. Table 3 shows that the multiple new-ranged Duncan's test indicated significant differences ($P < 0.05$) for the V_{UL} values among types B and A, and type E. However, there were no significant differences among the other groups. For V_{UR} values significant differences existed for types C and B and type A.

In conclusion, the above-mentioned results concerning the effects of plantation spacing on the sample trees, the experiment were conducted using the stress-wave and

Table 3. Results of multiple new-ranged Duncan's test for stress-wave velocity (V_{SL}, V_{SR}) and ultrasonic-wave velocity (V_{UL}, V_{UR}) for five plantation sites

Parameter	Data				
Plantation site	Type E	Type C	Type A	Type D	Type B
V_{SL} ($\times 10^3$) m/s	2.90 ± 0.02	3.20 ± 0.02	3.21 ± 0.01	3.23	3.52 ± 0.03
Significant difference*					
Plantation site	Type A	Type D	Type C	Type E	Type B
V_{SR} ($\times 10^3$) m/s	1.71	1.77	1.77 ± 0.01	1.81 ± 0.01	1.83 ± 0.01
Significant difference*					
Plantation site	Type E	Type D	Type C	Type A	Type B
V_{UL} ($\times 10^3$) m/s	3.28 ± 0.06	3.43 ± 0.02	3.44 ± 0.02	3.61 ± 0.05	3.81 ± 0.04
Significant difference*					
Plantation site	Type A	Type E	Type D	Type B	Type C
V_{UR} ($\times 10^3$) m/s	1.72 ± 0.01	1.74	1.77 ± 0.02	1.80 ± 0.02	1.81
Significant difference*					

Results are means ± SD
See Table 2 for other explanations
*$P < 0.05$

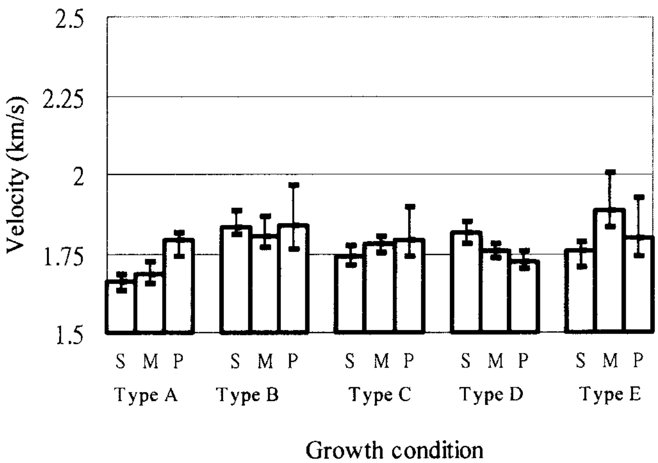

Fig. 6. Radial velocity of stress waves in trees with different growth conditions from various plantation spacing sites. See Fig. 5 for other explanations

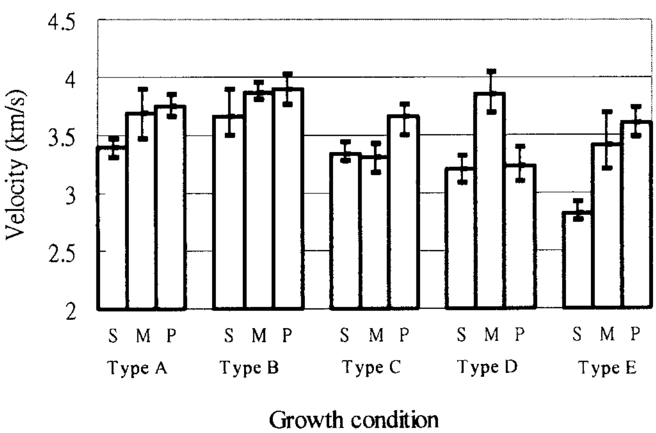

Fig. 7. Longitudinal velocity of ultrasonic waves in trees with different growth conditions from various plantation spacing sites. See Fig. 5 for other explanations

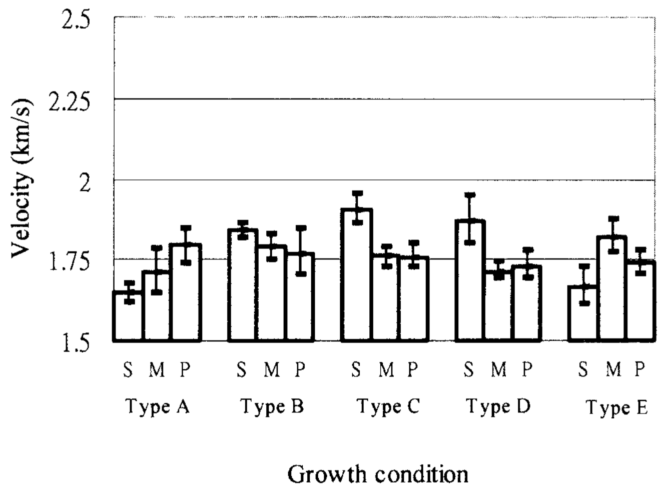

Fig. 8. Radial velocity of ultrasonic waves in trees with different growth conditions from various plantation spacing sites. See Fig. 5 for other explanations

ultrasonic-wave methods. The better quality of sample trees occurred in the type B spacing site. This is consistent with our previous research results.[14–17]

Effects of growth conditions on stress-wave and ultrasonic-wave velocities

To understand the effect of growth conditions on the stress-wave and ultrasonic-wave velocities, the relations between the DBH and stress-wave and ultrasonic-wave velocities are discussed. In the same age group the trees with large DBH values exhibited a greater growth rate and a higher frequency of cell division in the thickening growth. From Fig. 9 it is obvious that V_{SL} and V_{UL} values decreased linearly with increasing DBH values. The following negative linear regressions were obtained.

$$V_{SL} = -14.3D + 3310.9, \quad R^2 = 0.14, \quad F = 6.9$$
$$V_{UL} = -22.8D + 4233.8, \quad R^2 = 0.25, \quad F = 14.1$$

where D represents the DBH values of the sample trees. Although R^2 values were rather small, there was a significant difference at the $P < 0.05$ confidence level for V_{SL} and at the $P < 0.01$ confidence level for V_{UL} by F tests.

Wang and Chen[14] indicated that the percentage of latewood decreased linearly with increasing ring width obtained from 40-year-old sample trees from the same experimental forest site. This suggested that in an even-age stand the sample trees with high DBH values usually had a lower percentage of latewood, lower density and modulus of elasticity, and lower V_{SL} and V_{UL} values. However, the V_{SR} and V_{UR} values were not significantly affected by the DBH values in the sample trees.

Relation between stress-wave velocity and ultrasonic-wave velocity

From Fig. 10 it is obvious that the relation between stress-wave velocity and ultrasonic-wave velocity can be represented by the following positive linear regression formulas.

$$V_{UL} = 0.90V_{SL} + 726.9, \quad R^2 = 0.60, \quad F = 110.5$$
$$V_{UR} = 0.63V_{SR} + 738.8, \quad R^2 = 0.51, \quad F = 54.0$$

Significant difference, as showed by the F-value at the $P <$ 0.01 confidence level. V_{UL} values were 6%–13% larger than the V_{SL} values. This is in agreement with the results reported by Nakamura in which he indicated that the V_{UL} values for *Abies* spp. and *Larix* spp. were greater than the V_{SL}.[3] V_{UR} values were close to V_{SR} values.

Effects of plantation spacings on dynamic modulus of elasticity of standing trees

The sample trees in all growth conditions were considered collectively for the five plantation sites. The results of the multiple new-ranged Duncan's method are shown in Table 4. A decreasing order for E_{SL} (dynamic modulus of elasticity parallel to the grain obtained from stress waves) and E_{UL} (dynamic modulus of elasticity parallel to the grain

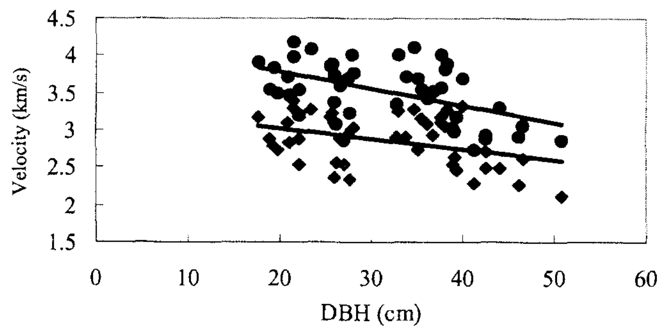

Fig. 9. Relations between the DBH and the longitudinal velocities of stress waves (*squares*) and ultrasonic waves (*circles*)

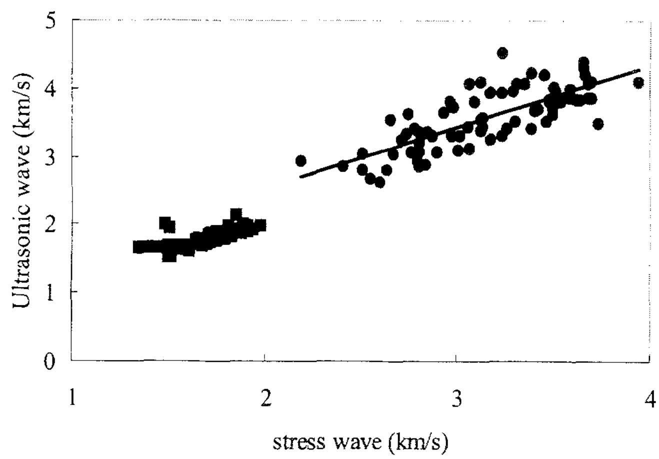

Fig. 10. Relations between the velocity of stress waves and ultrasonic waves in longitudinal and radial directions. *Circles*, longitudinal velocity; *squares*, radial velocity

Table 4. Results of multiple new-ranged Duncan's test for dynamic modulus of elasticity (E_{SL}, E_{SR}, E_{SL}, E_{UR}) for five plantation sites

Parameter	Data				
Plantation site	Type E	Type C	Type D	Type A	Type B
E_{SL} ($\times 10^3$) kgf/cm^2	82.70 ± 6.14	94.30 ± 4.18	99.70 ± 10.11	101.00 ± 1.12	128.00 ± 6.06
Significant difference*					
Plantation site	Type D	Type A	Type C	Type E	Type B
E_{SR} ($\times 10^3$) kgf/cm^2	26.80 ± 2.43	29.90 ± 2.65	32.20 ± 9.00	33.20 ± 2.18	35.70 ± 1.81
Significant difference*					
Plantation site	Type E	Type C	Type D	Type A	Type B
E_{UL} ($\times 10^3$) kgf/cm^2	99.30 ± 11.70	114.00 ± 8.98	117.00 ± 3.87	117.00 ± 6.51	147.00 ± 10.07
Significant difference*					
Plantation site	Type E	Type D	Type C	Type A	Type B
E_{UR} ($\times 10^3$) kgf/cm^2	28.20 ± 2.23	29.30 ± 2.43	30.50 ± 1.03	32.90 ± 1.70	33.00 ± 1.32
Significant difference*					

Results are means ± SD
See Table 2 for other explanations
*$P < 0.05$

obtained from ultrasonic waves) is as follows: type B > type A > type D > type C > type E. There is also a decreasing order in the E_{SR} values (dynamic modulus of elasticity perpendicular to the grain obtained from stress waves) as follows: type B > type E > type C > type A > type D. There were no significant differences among these five plantation sites for E_{UR} values (dynamic modulus of elasticity perpendicular to the grain obtained from ultrasonic waves). The E_{UL} values were 3.8%–11.6% larger than the E_{SL} values, and the E_{UR} values were 5.4%–15.0% less than the E_{SR} values.

In this study, although the values of the dynamic modulus of elasticity were calculated from the effective density (ρ_{eff}), which was adjusted using the K value (0.6 for stress wave, 0.7 for ultrasonic wave). The differences between E_{UL} and E_{SL} and between E_{UR} and E_{SR} were obtained.

Based on the above-mentioned results, it can be seen that the dynamic modulus of elasticity values obtained from sample trees grown at the type B site were higher than those for the other types. These results are in agreement with those reported by previous authors[14–17] in which type A and B plantation spaced lumber had greater wood density, larger latewood percentages, and longer tracheids. As a result, its strength was relatively greater. Our findings are also in agreement with those of Sumiya et al.,[20] who indicated that larger planting density stands exhibited increased wood densities and dynamic moduli of elasticity.

Effect of growth conditions on dynamic modulus of elasticity of standing trees

The relations between DBH and E_{SL} and E_{UL} values of sample trees were studied. From Fig. 11 it can be seen that the E_{SL} and E_{UL} values decreased linearly with increasing DBH. The following linear regressions were obtained.

$$E_{SL} = -1008.8D + 133216, \quad R^2 = 0.11, \quad F = 5.2$$
$$E_{UL} = -1471.5D + 165518, \quad R^2 = 0.18, \quad F = 9.3$$

Although the R^2 values were low, they were significant at the $P < 0.05$ confidence level for E_{SL} and at the $P < 0.01$ confidence level for E_{UL} by the F test. This suggested that the rapidly growing superior trees had a lower percentage of latewood and hence had low density values and lower stress-wave and ultrasonic-wave velocities. As a result, the modulus of elasticity and strength properties were rather low.

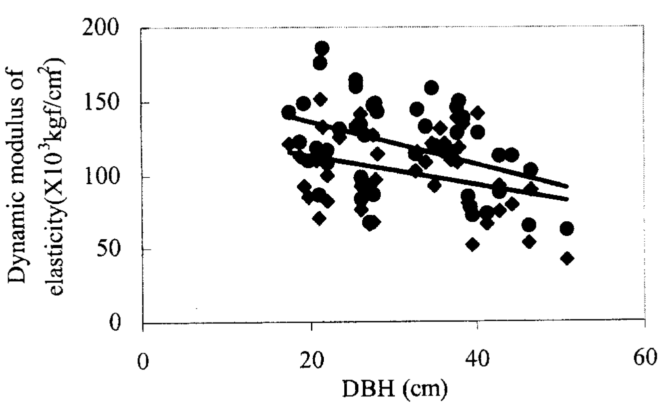

Fig. 11. Relations between the DBH and the dynamic modulus of elasticity of stress waves (*squares*) and ultrasonic waves (*circles*)

Conclusions

1. The variation in wood quality in sample trees during a growth season in a year was minimal.
2. Among the sample trees grown at five plantation sites with different spacing, V_{SL}, V_{UL}, E_{SL}, and E_{UL} values obtained from the type B site were significantly higher than those for other sites (A, C, D). The V_{SR} and E_{SR} values obtained from type B and E sites were significantly greater than those from type A and D sites.
3. The V_{SL}, V_{UL}, E_{SL}, and E_{UL} values decreased linearly with increasing DBH in the sample trees. In contrast, the V_{SR}, V_{UR}, E_{SR}, and E_{UR} values for the sample trees were not influenced significantly by the DBH.
4. The V_{UL} values were 6%–13% larger than those for V_{SL}. The V_{UR} values were close to the V_{SR} values.

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