RING CHARACTERISTICS AND COMPRESSIVE STRENGTH OF JAPANESE CEDAR TREES GROWN UNDER DIFFERENT SILVICULTURAL TREATMENTS

Song-Yung Wang
Professor

Jin-Hau Chen
PhD Candidate
School of Forestry and Resource Conservation
College of Agriculture, National Taiwan University
1 Roosevelt Rd., Sec. 4
Taipei 106, Taiwan

Kuang-Ping Hsu
Research Assistant
Division of Wood Cellulose
Taiwan Forestry Research Institute
53 Nan-Hai Rd.
Taipei 100, Taiwan

*Cheng-Jung Lin**
Associate Researcher
Division of Forest Utilization
Taiwan Forestry Research Institute
53 Nan-Hai Rd.
Taipei 100, Taiwan

Ming-Chen Jane
Assistant Research Fellow
School of Forestry and Resource Conservation
College of Agriculture, National Taiwan University
1 Roosevelt Rd., Sec. 4
Taipei 106, Taiwan

(Received January 2006)

Abstract. The effects of different plantation spacings and thinning treatments on the ring characteristics, compressive strength, and dynamic modulus of elasticity (DMOE) of Japanese cedar (*Cryptomeria japonica*) trees were investigated. The results revealed that young trees of more-closely spaced plantations (3000 trees/ha) had higher wood density and compressive strength than those of more-widely spaced plantations (2200 trees/ha). Different (first and second) thinning treatments of the 2 initial spacings had little effect on ring characteristics or compressive strength. Overall, the average ring characteristics, compressive strength, and DMOE of 35-yr-old Japanese cedar at different plantation spacings and thinning treatments showed no statistically significant differences. The results suggest that using these silvicultural treatments with a longer rotation age will have no detrimental effects on the wood density, compressive strength, or DMOE.

Keywords: Initial spacing; thinning; ring characteristics; compressive strength; dynamic modulus of elasticity.

INTRODUCTION

In Taiwan, where Japanese cedar (*Cryptomeria japonica*) was introduced and has been extensively planted, the wood quality of fast-growing trees has been improved by intensive silvicultural treatments. Japanese cedar is a dominant species of plantations and is currently an important timber resource in Taiwan.

In general, tree growth can be directly controlled

---

* Corresponding author: d88625002@yahoo.com.tw

Wood and Fiber Science, 40(3), 2008, pp. 384 – 391

by plantation techniques, including plantation spacing and thinning treatments, which are important practices for commercial plantation wood. However, it is generally recognized that the properties of wood may be affected by silvicultural techniques (Zobel and van Buijtenen 1989). Traditionally, individual silvicultural studies have concentrated on the wood properties of trees following various treatments. Research is lacking on tree properties resulting from different spacings produced by various thinning treatments. The effective utilization of wood requires an understanding of the effects of thinning treatments on wood properties.

As a result of different intensive silvicultural treatments carried out before rotation, wood properties of plantations may have changed. Pape (1999) indicated that during the latter stage of stand development, when mature wood forms, thinning affects tree growth, which in turn affects wood properties. Wang and Lin (1996) and Wang and Ko (1998) indicated that the smaller initial spacing of Japanese cedar trees produced larger values of wood density, bending strength, and modulus of elasticity compared with greater spacing. Investigations of Taiwania (*Taiwania cryptomerioides*), balsam fir (*Abies balsamea*), Douglas fir (*Pseudotsuga menziesii*), and jack pine (*Pinus banksiana*) showed that an increase in the thinning intensity is followed by reductions in wood density, bending modulus of elasticity, and bending strength (Jozsa and Brix 1989; Barbour et al 1994; Koga et al 2002; Wang et al 2003). Most forest scientists recognize that there are strong correlations and feedback mechanisms among variables that are used to describe the relationships of lumber bending stiffness and strength with tree growth characteristics (Lei et al 2005). Pape (1999) indicated that with an increasing thinning intensity, the basic density of the entire cross-section decreases in Norway spruce (*Picea abies*). However, the effects of silvicultural treatments on wood properties encompass many factors and responses that increase, decrease, or have no effect on the wood density and strength (Zobel and van Buijtenen 1989; Zobel and Sprague 1998). Therefore in the present study, we investigated the effects of plantation spacing and thinning treatments on the ring characteristics, compressive strength, and dynamic modulus of elasticity (DMOE) of Japanese cedar trees using X-ray scanning, a fractometer, and an ultrasonic-wave method. The results provide information for forest management and utilization of Japanese cedar wood.

MATERIAL AND METHODS

The experimental plantations are located in compartment 28, Dui-Gao-Yue plantation area, He-She Working Station of the Experimental Forest of National Taiwan University, in Nantou County, central Taiwan. The elevation is 1825 m, and the mean weather conditions are 16°C, 90% RH, and 2100 mm of precipitation.

The area of this study site was about 13.1 ha. It was divided into 6 plots, each of 2.1 ha, including a buffer zone. In this experiment, all trials were set up according to a randomized block design. The study plantation was planted in 1969. Two plantation spacings of 2200 (type A) and 3000 (type B) trees/ha used in this experiment were carried out when the trees were 22 yr old (ie in 1991). The first (low) thinning treatment resulted in basal areas of 28.3 and 35.0 m^2/ha at breast height. A second different thinning treatment was implemented in 2001 at about 32 yr, resulting in basal areas of 25.1 and 34.5 m^2/ha at breast height. The residual trees with these 6 stand densities (plots) (with initial spacing and two thinning treatments) are shown in Table 1.

TABLE 1. *Structure of various plantation spacing and thinning treatments of the sampled Japanese cedar trees.*

Treatment code	Age (yr)	Density (trees/ha)	Mean DBH (cm)	Basal area (m^2/ha)
Type A	22	2200	21.9	83.2
	23–32	550	25.6	28.3
	33–36	340–512	27.6	25.1
Type B	22	3000	20.6	100.1
	23–32	750	24.3	35.0
	33–36	612–738	25.8	34.5

DBH, diameter at breast height.

The diameter at breast height (DBH) of each tree on the 6 plots was measured. Mean DBH values of trees from different stand densities are shown in Table 1. Average DBH values between different silvicultural treatments of types A and B showed no significant differences.

Thirty mean DBH readings from trees were taken from each plot, and 180 sample trees in total were sampled for ultrasonic wave testing. A commercially available ultrasonic testing tool (Sylvatest Duo, 22 kHz, Concepts Bois Structure, Switzerland) was used to evaluate the standing trees (at breast height). The ultrasonic wave velocity and DMOE in the direction parallel to the grain of the trees were calculated. A flowchart outlining this study is shown in Fig 1.

The ultrasonic wave velocity (V) and the DMOE were calculated from the following formulas:

$$V = L/T \tag{1}$$

and

$$\mathrm{DMOE} = V^2 \times D/g; \tag{2}$$

where V is the ultrasonic wave velocity in the direction parallel to the grain of trees (m/s), L is the distance between the 2 transducers (m), T is the propagation time of the pulse from the transmitting transducer to the receiving transducer(s), DMOE is the direction parallel to the grain (MPa), D is the density of wood in the sample tree (kg/m^3), and g is the gravitational constant (6.67300×10^{-11} m^3 kg^{-1} s^{-2}).

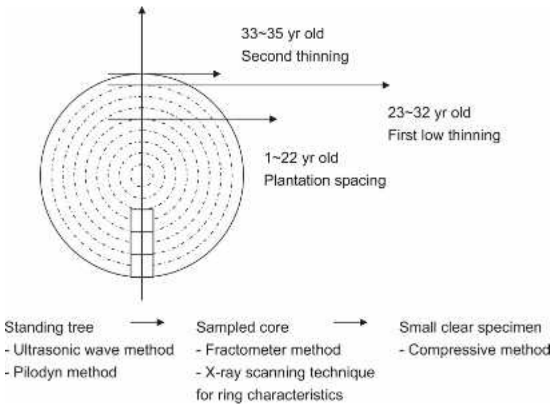

FIGURE 1. Schematic of the experimental materials procedure.

After ultrasonic wave testing, the Pilodyn method was used to evaluate the penetration depth of wood with a striker pin at a fixed energy of 6 J. The probe in this study was 3-mm dia and 40-mm length, and was used inside-bark at DBH. Since it was used on the tangential face of the trees, its penetration direction was always radial. In addition, the penetration depth (mm) was displayed on the meter screen and recorded, and the average penetration depth of each tree was determined.

After ultrasonic wave and Pilodyn testing, an increment borer was used to extract 5-mm-dia cores. From the eastern aspect of each sample tree, we extracted 2 pith-to-bark increment-core specimens for the fractometer measurement and X-ray scanning at DBH (in the same direction) in 2005, when the trees were about 35 yr old.

After taking the core specimens, 3 mean-diameter trees were selected from each plot, and 18 sample trees in total were cut. One 100-mm-thick cross-sectional disc was cut from each sample tree at the position of its DBH. A diametrical strip (passing through the pith) was sawn from each disc, and then small clear specimens (20 × 20 × 40 mm, radial × tangential × longitudinal) were cut from the strip. The core and small clear specimens were taken from the same direction and near the position at breast height.

The increment cores and small clear specimens were conditioned in a controlled environment (12% EMC: 20°C and 65% RH). Measurements were made on the treated core after conditioning for 2 mo.

The compressive strength parallel to the grain was assessed using a fractometer (on core specimens) and universal-type testing machine (on small clear specimens). A commercially available fractometer (Type II, IML, Germany) was used to evaluate the compressive strength of increment cores every 6 mm from pith to bark. The fractometer is a device that breaks a radial increment core to measure the fracture strength along the fibers (longitudinal compressive strength). A cylindrical specimen was inserted into the jaws so that the fibers were parallel to the direction of loading.

For X-ray scanning, the ring characteristics of extracted (using distilled water and alcohol-benzene) and conditioned strips were analyzed by a QTRS-01X Tree Ring Analyzer (Quintek Measurement Systems (QMS), Knoxville, TN). The strips were scanned in the radial direction. Dimensions of the standard collimator were 0.038 mm wide and 1.59 mm high at the detector. The increment of the sample step-size was 0.02 mm. The determination of density was based on the relationship of X-ray attenuation and density (QMS 1999).

The absorption of X-rays was determined in a controlled energy range. This was related to the actual sample density (at 12% moisture content). The equipment was calibrated to the actual sample density. The boundary of the earlywood (EW) and latewood (LW) was determined by a comparator, and the location was then converted into a density threshold in the density profile. The ring density boundary (its location and density value) was identified by a floating density threshold. Based on the density profiles, the EW and LW boundary was defined in each ring by an average density for the maximum and minimum densities in a ring. These data were input into the tree-ring analysis program (as a part of the QMS). The following characteristics were derived: average ring width, EW width, LW width, ring density, EW density, LW density, maximum density, minimum density, and LW percentage in a ring across the sample.

The cambium ages of the sample specimens were differentiated into 1–22, 23–32, 33–35, and 1–35 (overall) yr, to correspond to exposure to the different silvicultural regimes (ie plantation spacing, first low thinning, second different thinning, and overall treatments) for the tests.

RESULTS AND DISCUSSION

Wood Density

Average wood densities of small clear specimens cut from the 22-yr-old trees subjected to 2 initial stocking densities of 2200 (type A) and 3000 (type B) trees/ha were analyzed, and the results are shown in Table 2. According to the statistical analysis, the average value of the wood density of type B was significantly greater than that of type A (486 vs 462 kg/m^3).

Average wood densities of specimens cut from 23- to 32-yr-old trees subjected to the first thinning densities of 28.3 and 35.0 m^2/ha (basal area) were analyzed, and results are shown in Table 3. Average wood densities between the 2 thinning densities of types A and B did not differ significantly.

In the Macdonald and Hubert (2002) review, they stated that there is general agreement that trees planted at a wider initial spacing tend to have larger crown diameters, larger knots, increased ring widths, and reduced average wood densities. Pape (1999) indicated that in response to changes in thinning treatment, the focus of wood production shifts from suppressed trees to dominant ones. Some studies reported that thinning causes a slight decrease in wood density for *Pinus radiata* and *Pseudotsuga menziesii* (Cown 1974; Erickson and Harrison 1974; Barbour et al 1994). Others indicated that thinning had no or minor effects on the wood density of *Pinus pinaster*, *Pinus radiata*, *Pinus taeda*, and *Larix leptalepis* (Nicholls 1971; Cown 1973; Trylor and Barton 1982; Moschler et al 1989). Similar results have been reported for the EW and LW

TABLE 2. *Density and compressive strength of the 2 initial plantation spacings of 22-yr-old sugi plantations.*

Properties	Type A	Type B
D (kg/m^3)	462.7^a	486.0^b
σ_{cm} (MPa)	33.80^a	36.69^b
σ_{cf} (MPa)	32.41^a	37.64^b

D, density; σ_{cm}, compressive strength parallel to the grain using a universal-type testing machine; σ_{cf}, compressive strength parallel to the grain using a fractometer.

Means within a given column with a different letter significantly ($p \leq 0.05$) differ as determined by the *t*-test.

densities of Douglas-fir (Megraw and Nearn 1972).

Compressive Strength

A comparison of average compressive strength values of young Japanese cedar plantation specimens under the 2 initial stocking densities is shown in Table 2. A significant difference ($p < 0.05$) existed for the compressive strength of specimens between types A and B. This result indicates that the initial stocking density of 3000 trees/ha produced larger compressive strength values (36.69, 37.64 MPa) than that of 2200 trees/ha (33.80, 32.41 MPa).

In this experiment, the average wood densities of young Japanese cedar in the 2 initial stocking densities (2200 and 3000 trees/ha) showed a statistically significant difference. Moreover, more-closely spaced plantations produced wood with higher compressive strength than more-widely spaced plantations.

A comparison of compressive strength values for the 2 first low-thinning treatments is shown in Table 3. There was no significant difference between the stand densities of 28.3 (type A) and 35.0 m^2/ha (type B). Therefore, the first low-thinning treatments of the 2 initial spacing levels had little effect on wood density or compressive strength. Likewise, a comparison of compressive strength values for the different thinning treatments (after the second thinning) is shown in Table 4. There was no significant difference between the stand densities of 25.1 (type A) and 34.5 m^2/ha (type B). Therefore, the second thinning treatments of the 2 initial spacing levels had little effect on compressive strength.

The relationship between the compressive strength and diameter at breast height (DBH) of sampled trees was examined. It was clear that the compressive strength values increased linearly with decreasing DBH, and the relationship could be expressed by the following linear regression:

TABLE 3. *Density and compressive strength of the 2 plantation spacings and low-thinning treatment for 23- to 32-yr-old sugi trees.*

Properties	Type A	Type B
D (kg/m^3)	459.6	487.0
σ_{cm} (MPa)	36.26	39.73
σ_{cf} (MPa)	34.30	39.77

TABLE 4. *Compressive strength of the 2 plantation spacing levels and thinning treatments for 33- to 36-yr-old sugi trees.*

Compressive strength	Type A	Type B
σ_{cf} (MPa)	34.11	39.34

$$\text{Compressive strength} = -1.57 \times \text{DBH} + 781.1,\quad R^2 = 0.33,\quad F = 78.1^{**}.$$

The compressive strength values of Japanese cedar increased with an increase in the wood density. Their relationship could be represented by the following positive linear regression formula:

$$\text{Compressive strength} = 0.08 \times \text{wood density} - 1.26,\quad R^2 = 0.55,\quad F = 444.2^{**}.$$

There were significant differences ($p < 0.01$) according to the F test. This is similar to the result reported earlier by Wang and Chen (1992) and Chuang and Wang (2001), who indicated that in an even-aged stand, Japanese cedar trees with high DBH values usually had a lower density, lower bending properties, and lower compressive strength. Lin et al (2007) reported that ring density was related to compressive strength, but was not the sole factor affecting the wood strength. Moreover, compressive strength is affected by various ring characteristics.

Ring Characteristics

Nine ring characteristics of Japanese cedar cores obtained from the 2 initial stocking densities are shown in Table 5. Average values of the ring density, minimum density, and LW percentage in a ring of type B (3000 trees/ha) were significantly greater than those of type A (2200 trees/ha). However, the average ring width, EW width, LW width, EW density, LW density, and maximum density in a ring with the 2 initial

TABLE 5. *Comparison of ring characteristics of the 2 initial plantation spacings of 22-yr-old sugi plantations.*

Ring characteristics	Type A	Type B
Width (mm)		
Ring	5.28	5.66
Earlywood	3.95	3.67
Latewood	1.32	1.99
Density (kg/m^3)		
Ring	498.6^a	574.9^b
Earlywood	390.2	455.3
Latewood	828.1	819.1
Minimum	304.2^a	373.4^b
Maximum	1025.6	986.6
Latewood percentage	25.0^a	35.2^b

Means within a given column with different letters significantly ($p \leq 0.05$) differ as determined by the *t*-test.

stocking densities revealed no significant differences between types A and B.

Nine ring characteristics of Japanese cedar cores obtained from different thinning treatments (first and second) are shown in Tables 6 and 7. Average ring width, EW width, LW width, ring density, EW density, LW density, maximum density, minimum density, and LW in a ring with the different thinning treatments revealed no significant differences between types A and B. Overall, the average ring characteristics of 35-yr-old Japanese cedar with different silvicultural treatments showed no statistically significant differences.

Koga and Zhang (2002) reported that the wood density generally tends to decrease with increasing ring width. Dutilleul et al (1998) reported that the well-established negative relationship between ring width and wood density was observed only for slow-growing Norway spruce. However, no such relationship was observed in fast-growing trees. Ring density is significantly affected by stem position, tree age, growth traits, genetic factors of the trees, environmental conditions of the site, and silvicultural practices (Zobel and van Buijtenen 1989; Dutilleul et al 1998; Koga and Zhang 2002).

TABLE 6. *Comparison of ring characteristics of the 2 plantation spacings and low-thinning treatment for 23- to 32-yr-old sugi trees.*

Ring characteristics	Type A	Type B
Width (mm)		
Ring	1.75	2.13
Earlywood	1.33	1.48
Latewood	0.43	0.65
Density (kg/m^3)		
Ring	461.3	501.1
Earlywood	340.3	358.8
Latewood	841.1	824.3
Minimum	258.1	271.6
Maximum	979.7	954.4
Latewood percentage	24.6	30.5

TABLE 7. *Comparison of ring characteristics of the various plantation spacing levels and thinning treatments for 33- to 36-yr-old sugi trees.*

Ring characteristics	Type A	Type B
Width (mm)		
Ring	1.58	1.55
Earlywood	1.09	1.01
Latewood	0.49	0.54
Density (kg/m^3)		
Ring	512.8	566.1
Earlywood	378.8	405.9
Latewood	841.3	840.4
Minimum	305.4	334.7
Maximum	950.2	967.7
Latewood percentage	31.0	34.8

Dynamic MOE and Penetration Depth

The DMOE and Pilodyn penetration depth of Japanese standing trees (represented by each 35-yr-old sampled tree) grown with different initial spacing and thinning treatments were investigated using the Sylvatest ultrasonic wave and Pilodyn techniques. Comparisons of the DMOE and penetration depth values for various silvicultural treatments are shown in Table 8. The

TABLE 8. *Density, compressive strength, dynamic modulus of elasticity, and penetration depth of the various plantation spacings and thinning treatments for 35-yr-old sugi trees.*

Properties	Type A	Type B
D (kg/m^3)	463.0	485.2
σ_{cm} (MPa)	35.7	38.7
σ_{cf} (MPa)	33.8	39.5
V (m/sec)	2366.3	2677.5
DMOE (MPa)	2624.2	3466.9
P (cm)	19.5	17.9

V, ultrasonic wave velocity, DMOE, dynamic modulus of elasticity; P, penetration depth by Pilodyn tool.

results revealed no significant differences between types A and B.

Overall comparisons of the wood density and compressive strength of 35-yr-old Japanese cedar trees grown with different silvicultural treatments are shown in Table 8. The results also revealed no significant differences between types A and B.

Although the wood density and compressive strength of young Japanese cedar trees (juvenile wood) grown with 2 initial spacings differed, the wood properties after 23 yr were not affected. Moreover, overall wood properties of sampled specimens from 35-yr-old trees grown under different silvicultural treatments were analyzed, and no significant differences were detected between types A and B. Therefore, we suggest that these silvicultural practices can be used without concern for declining wood density, compressive strength, or modulus of elasticity. A longer rotation age of forest management to reduce the juvenile wood content should be considered due to the decreasing influence of young trees on wood density and compressive strength.

CONCLUSIONS

In this study, the ring characteristics, compressive strength, and DMOE at breast height of Japanese cedar (*Cryptomeria japonica*) trees grown with different plantation spacing and thinning treatments were investigated. The results are summarized as follows.

1. The average wood density of young 22-yr-old Japanese cedar at the 2 initial stocking levels showed a statistically significant difference. Moreover, more-closely spaced plantations trees had higher compressive strength compared with those grown on more-widely spaced plantations.
2. Different first and second thinning treatments of the 2 initial spacing densities had little effect on the wood density or compressive strength of mature Japanese cedar (23–35 yr old).
3. Overall, the average ring characteristics, compressive strength, DMOE, and penetration depth of 35-yr-old Japanese cedar at different plantation spacing and thinning treatments showed no statistically significant differences. The results suggest that these silvicultural treatments with a longer rotation age can be carried out with little detrimental effect on wood density, compressive strength, or modulus of elasticity.

ACKNOWLEDGMENTS

The authors wish to thank the Taiwan Forestry Research Institute and the National Science Council for the financial support (96AS-7.2.3-FI-G1 and NSC 92-2313-B-002-119).

REFERENCES

Barbour RJ, Fayle DCF, Chauret G, Cook J, Krsh MB, Ran S (1994) Breast-height relative density and radial growth in mature jack pine (*Pinus banksiana*) for 38 years after thinning. Can J For Res 24:2239–2247.

Chuang ST, Wang SY (2001) Evaluation of standing tree quality of Japanese cedar grown with different spacing using stress-wave and ultrasonic-wave methods. J Wood Sci 47(4):245–253.

Cown DJ (1973) Effects of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine. N Z J For Sci 3:379–389.

——— (1974) Comparison of the effects of two thinning regimes on some wood properties of radiata pine. N Z J For Sci 4:540–551.

Dutilleul P, Herman M, Avella-Shaw T (1998) Growth rate effects on correlations among ring width, wood density, and mean tracheid length in Norway spruce (*Picea abies*). Can J For Res 28:56–68.

Erickson HD, Harrison AT (1974) Douglas-fir wood quality studies. V. Effects of age and stimulated growth on wood density and anatomy. Wood Sci Technol 8:207–226.

Jozsa LA, Brix H (1989) The effects of fertilization and thinning on wood quality of a 24-year-old Douglas-fir stand. Can J For Res 19:1137–1145.

Koga S, Zhang SY (2002) Relationships between wood density and annual growth rate components in balsam fir (*Abies balsams*). Wood Fiber Sci 34(1):146–157.

———, Begin J (2002) Effects of recommercial thinning on annual radial growth and wood density in balsam fir (*Abies balsamea*). Wood Fiber Sci 34:625–642.

Lei YC, Zhang SY, Jiang Z (2005) Models for predicting lumber bending MOR and MOE based on tree and stand characteristics in black spruce. Wood Sci Technol 39:37–47.

Lin CJ, Tsai MJ, Lee CJ, Wang SY, Lin LD (2007) Effects of ring characteristics on the compressive strength and dynamic modulus of elasticity of seven softwood species. Holzforschung 61(3):414–418.

Macdonald E, Hubert J (2002) A review of the effects of silviculture on timber quality of Sitka spruce. Forestry 75:107–138.

Megraw RA, Nearn WT (1972) Detailed DBH density profiles of several trees from Douglas-fir fertilizer/thinning plots, Proceedings of the Symposium, on the Effect of Growth Acceleration on the Properties of Wood. Madison, WI: USDA Forest Service. 22 pp.

Moschler WW, Dougal EF, McRae DD (1989) Density and growth ring characteristics of *Pinus taeda* L. following thinning. Wood Fiber Sci 21:313–319.

Nicholls JWP (1971) The effects of environmental factors on wood characteristics. 2. The effect of thinning and fertilizer treatment on the wood of *Pinus pinaster.* Silvae Genet 20:67–73.

Pape R (1999) Effects of thinning regime on the wood properties and stem quality of *Picea abies.* Scand J For Res 14:38–50.

QMS (1999) QMS tree ring analyzer users guide model QTRS-01X. Knoxville, TN: Quintek Measurement Systems.

Trylor FW, Barton JD (1982) Growth ring characteristics, specific gravity, and fiber length of rapidly grown loblolly pine. Wood Fiber Sci 14:204–210.

Wang SY, Chen KN (1992) Effects of plantation spacings on tracheid lengths, annual-ring widths, and percentages of latewood and heartwood of Taiwan-grown Japanese cedar. Mokuzai Gakkaishi 38:645–656.

———, Chiu CM, Lin CJ (2003) Application of the drilling resistance method for annual ring characteristics evaluation of Taiwania (*Taiwania cryptomerioides* Hay.) trees grown in different thinning and pruning treatments. J Wood Sci 49:116–124.

———, Ko CY (1998) Dynamic of elasticity and bending properties of large beams of Taiwan-grown Japanese cedar from different plantation spacing sites. J Wood Sci 44:62–68.

———, Lin SH (1996) Effects of plantations spacings on the quality of visually graded lumber and mechanical properties of Taiwan-grown Japanese cedar. Mokuzai Gakkaishi 42:435–444.

Zobel BJ, van Buijtenen JP (1989) Wood variation its cause and control. Bruhlsche, Berlin, and Heidelberg, Germany: Springer-Verlag. Pp. 218–248.

———, Sprague JR (1998) Juvenile wood in forest trees. Berlin and Heidelberg, Germany: Spring-Verlag. Pp. 26–38.