EFFECTS OF PLANTING DENSITY ON VISUALLY GRADED LUMBER AND MECHANICAL PROPERTIES OF TAIWANIA

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ABSTRACT

The purpose of this study was to investigate the effects of planting density on the quality of visually graded lumber, and the strength properties of 35-year-old Taiwania (*Taiwania cryptomerioides* Hay). The results are summarized as follows.

(1) Lumber obtained from the site with type S planting density (6940 trees/ha) were mostly of better grade (84.6% including first and second grades), followed by type Q (2500 trees/ha) (69.1%), type R (3300 trees/ha) (62.5%), whereas poorer lumber was found mostly from trees with type P planting density (1000 trees/ha) (41.6%).

(2) Specimens cut from trees of type S planting density site had the largest average values of ultrasonic velocity (Vu), dynamic modulus of elasticity obtained from transversal vibration (Edt), dynamic modulus of elasticity obtained from ultrasonic velocity (Edu), modulus of elasticity at bending (MOE), and modulus of rupture at bending (MOR), followed in decreasing order by those of type P, type R, and type Q sites.

(3) Interrelations between Vu, Edu, Edt, MOE, and MOR can be represented by positive linear regression formulas. The differences were highly significant.

Keywords: Taiwania, planting density, visually graded lumber, ultrasonic wave velocity, dynamic modulus of elasticity, bending properties (MOE, MOR).

INTRODUCTION

Because trunks contribute most wood for utilization, the objective of silivicultural practices should be geared toward producing wood of maximum volume and straight forms. Reducing the planting density (i.e. increasing the spacing) may increase the effective volume growth of a single tree, but the total volume growth per unit plantation area may be decreased. (Zobel and van Buijtenen 1989)

Previous investigations on the wood quality of *Cryptomeria japonica* trees grown at five sites with different plantation spacings (Wang and Chen 1992; Wang and Lin 1994, 1996; Wang and Ko 1998; Chuang and Wang 2001) indicate that the values for density, bending strength (modulus of rupture, or MOR), dynamic modulus of elasticity (E_D), and compression strength of wood cut from trees obtained from the nar-

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rower plantation spacing sites of type A (1 × 1 m, 10000 trees/ha) and type B (2 × 2 m, 2500 trees/ha) were higher than those of wood obtained from wider plantation spacing sites of type D (4 × 4 m, 630 trees/ha) and type E. (5 × 5 m, 400 trees/ha)

Wang and Lin also indicated that first-grade log and first-grade lumber with highest specific gravity, E_D, modulus of elasticity (MOE), and MOR values were observed in trees obtained from type A plantation spacing sites. The lowest values were found in those cut from type E site. The E_D, MOE, and MOR values for visually graded special-grade lumber were significantly higher than those for second- and third-grade lumber.

The purpose of this study was to investigate the effects of planting density on the quality of visually graded lumber, and the strength properties of 35-year-old Taiwania (*Taiwania cryptomerioides* Hay). The interrelationships between lumber grades and their strength properties were also examined.

MATERIALS AND METHODS

Conditions of experimental forest sites

The experimental sites were located in No.55-1 plot, second branch station, Chi-Tou Working Station of the Experimental Forest of National Taiwan University. The Taiwania trees were planted in 1966. Twelve small rectangular sites of 0.1 hectare each were established. They were divided into four different planting density sites as follows: type P, 3 × 3 m (1000 trees/ha); type Q, 2 × 2 m (2500 trees/ha); type R, 1 × 3 m (3300 trees/ha); and type S, 1.2 × 1.2 m (6940 trees/ha), and each treatment was performed three times on each site.

Preparation of specimens

The diameter at breast height (DBH) and tree height of each tree grown on the 12 small sites were measured, one mean-diameter tree was selected from each site, for a total of 12 sample trees. Each sample tree was cut into logs at 2.5-m intervals from the base to the top. After the grade of each log was determined, they were further band-sawn into lumber sequentially from the north side to the south side of the stem using the cant sawing method (Wang 1990). All large-beam specimens were 2.5 m long, 10 cm wide, and 5 cm thick. Most of the specimens used in this study came from the longitudinal-tangential plane. The diameter of logs varied with the planted density, and the tree height position changed; therefore the numbers of specimens obtained from sites of various planting density and tree height position were different. The specimens were kept in a temperature-controlled room at 20°C and relative humidity (RH) of 65%. When the moisture content reached 12%–13%, then the actual size and mass of each specimen were measured to obtain the density in the air-dried condition.

Visual grading of lumber

The visual grading of specimens was conducted according to CNS14631 (Chinese National Standard 14631, 2002) structural sawn lumber used in platform construction). The specimens were classified into three grades: construction grade (A), standard grade (B), and utility grade (U). Wood not meeting utility grade standards was classified as out-grade (H).

Ultrasonic and transverse vibration tests

The ultrasonic wave velocity propagated along the longitudinal direction of the specimens was measured by an ultrasonic meter (Sylvatest, frequency 16 KH_z, Swiss products) to calculate the dynamic modulus of elasticity (Edu). A Metriguard Model 340 Transverse Vibration Tester was used to measure the transversal vibration from which the undamped natural frequency was used to calculate the dynamic modulus elasticity (Edt) of each specimen (Wang and Lin 1996).

Static bending tests

The static bending tests were conducted in accordance with the third point loading method

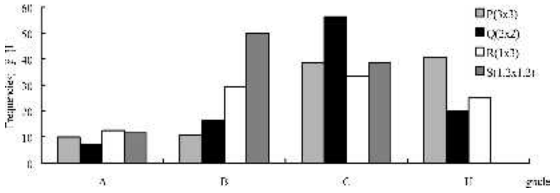

FIG. 1. The frequency of different visually graded lumber in different planting density sites.

using a Shimadzu UH-10A type testing machine. The span was 150 cm, and distance between the two loading points was 50 cm. The proportional limit, ultimate load, and deflection were obtained from the load-deflection curves, and these were used to calculate MOE, and MOR.

RESULTS AND DISCUSSION

Effects of planting density on lumber grades

The large-beam specimens were graded visually according to the standard of CNS14631 (2002). Very low frequencies in construction grade (A) lumber were found in trees from the four different spacing sites as shown in Fig. 1 and Table 1. Furthermore, there were no significant differences among these four (S, R, Q, P) sites. The number of pieces graded are also shown in Fig. 1 and Table 1. The frequencies of standard grade (B) lumber in decreasing order were type S (50%) > type R (29.2%) > type Q (16.4%) > type P (10.9%).

According to these findings, the better grade (including construction and standard grades) lumber produced from these four types of sites in decreasing order was type S (61.5%) > type R (41.7%) > type Q (23.7%) > type P (20.8%). This is because the lumber cut from trees with type S planting density (the narrowest spacing) site had smaller and fewer knots and consequently yielded better grades. On the contrary, the lumber cut from trees with the type P (the largest spacing) planting density site had more and larger knots and was obviously of relatively poorer grades. This is similar to previous results reported in the literature (Wang and Lin 1994, 1996; Wang and Ko 1998).

Zhang et al. (2002) indicated that the black spruce (*Picea mariana*) grown in initial spacings of 3086, 2500, and 2066 trees/ha have quite comparable Select Structural (SS) grade yields partly due to the relatively small branches. When the initial spacing is reduced further to 1372 trees/ha, however, a significant decrease in SS grade yield due to knots is expected.

Effects of planting density on in-grade lumber

Table 1 shows the analysis results of the multiple new-range Duncan statistical test. In terms

TABLE 1. *Analysis of multiple new-range Duncan's test of MOE and MOR for lumber graded by CNS14631 of the four planting density sites.*

Lumber grades	Planting density site	P (3 × 3)	Q (2 × 2)	R (1 × 3)	S (1.2 × 1.2)
Construction grade	Number of specimens	10	4	6	3
	Average MOR (MPa)	56.8 a[1]	58.1 a	61.9 a	52.9 a
	Average MOE ($\times 10^3$ MPa)	11.2 a	10.6 a	12.7 a	10.6 a
Standard grade	Number of specimens	11	9	14	13
	Average MOR (MPa)	46.6 a	52.4 a	47.0 a	50.0 a
	Average MOE ($\times 10^3$ MPa)	9.5 a	11.0 a	9.4 a	10.2 a
Utility grade	Number of specimens	39	31	16	10
	Average MOR (MPa)	48.4 a	45.4 a	48.1 a	50.7 a
	Average MOE ($\times 10^3$ MPa)	9.8 ab	9.0 a	9.5 ab	10.5 b
Out grade	Number of specimens	41	12	11	0
	Average MOR (MPa)	45.7 a	46.3 a	47.6 a	
	Average MOE ($\times 10^3$ MPa)	9.3 a	9.2 a	9.0 a	

Note: Number of samples of each planting density site: P: 101, Q: 56, R: 47, S: 26.

[1] Values sharing the same letter are not significantly different at the 0.05 level.

of construction grade (A), utility grade (U), and out-grade (H) lumber, no significant differences (0.05 level) in values of MOR and MOE were found among the four sites (types S, P, R, and Q). As for standard grade lumber (B), the MOE values of specimens obtained from type S site were significantly greater than those of the other three types (P, R, Q). However, significant differences among these three types (P, R, Q) were not observed. The MOR values of the four types (S, P, R, Q) showed no significant difference.

Effects of planting density on wood properties

The number of pieces tested for MOR and MOE of Taiwania within each type (S, Q, R, P) of planting density sites are shown in Table 2. The values of lumber cut from trees of type S site showed the largest average MOR values and smallest coefficient of variation (CV) values (CV = 13.1%). As seen in Table 2, the CV values for trees from type Q, P, and R sites ranged from 19.9% to 25.5%. Significant differences (0.05 level) in the MOR values among the four type sites (S, Q, R, P) were not observed.

The average MOE value (10.35×10^3 MPa) of lumber cut from trees of type S site also was the greatest, while the CV value (15%) was the lowest. However, according to the results of the multiple new-range Duncan test shown in Table 2, significant differences (0.05 level) existed between type S and Q sites, but not among the other three type sites.

In regard to the values of ultrasonic velocity (Vu), the specimens cut from trees of type S (narrowest spacing) site showed the largest average value (5224.1 m/s) and the lowest CV value (4.7%). As seen in Table 2, significant differences (0.05 level) existed between type S and P (largest spacing) sites, but not among the other type sites.

In regard to the values of Edt (dynamic modulus of elasticity calculated from transverse vibration test), Edu (dynamic modulus of elasticity calculated from ultrasonic velocity Vu), the specimens cut from trees of type S site had the largest average Edt and Edu values and the lowest CV values. Table 2 shows significant differences in Edt values between type S and Q sites. However, no significant differences among the other type sites were observed. In addition, no significant differences in Edu values were found among the four type sites.

As seen in Table 2, the average values of wood densities of air-dried (12% of moisture content) specimens (ρ_u) from the trees cut from the four different planting densities show no significant differences among these four type sites. This is likely because the better grade lumber (including construction and standard grade) cut

TABLE 2. *Analysis of multiple new-range Duncan's test of ρ_u, Edt, Edu, MOE and MOR for the four planting density sites.*

Planting density site	P (3 × 3)	Q (2 × 2)	R (1 × 3)	S (1.2 × 1.2)
Average density (g/cm^3) (ρ_u)	0.420 a[1]	0.414 a	0.416 a	0.411 a
CV%	6.3	7.5	8.9	6.3
Average Vu (m/s)	4999.7 a	5051.6 ab	5027.4 a	5224.1 b
CV%	10.0	6.8	8.6	4.7
Average Edt (×10^3 MPa)	8.9 ab	8.8 a	9.0 ab	9.6 b
CV%	16.4	17.0	23.7	12.3
Average Edu (×10^3 MPa)	10.8 a	10.6 a	10.7 a	11.3 a
CV%	16.0	16.1	22.8	11.7
Average MOR (MPa)	48.0 a	47.9 a	49.1 a	50.6 a
CV%	19.9	23.3	25.5	13.1
Average MOE (×10^3 MPa)	9.7 ab	9.5 a	9.6 ab	10.4 b
CV%	18.2	17.8	23.5	15.0

Note: Number of samples of each planting density site: P: 101, Q: 56, R: 47, S: 26.
[1] Values sharing the same letter are not significantly different at the 0.05 level.

from trees of type S site had higher frequencies than those of other type sites (Fig. 1).

According to the above-mentioned results, the Vu, Edt, Edu, MOR, and MOE values obtained from sample trees grown in type S site were higher than those of the other type sites. These results are in agreement with those previously reported (Wang and Chen 1992; Wang and Lin 1994, 1996; Wang and Ko 1998), that is, types A (1 m × 1 m) and B (2 m × 2 m) plantation-spaced lumber had greater wood density, larger latewood percentages, and longer tracheids. As a result, the strength was relatively greater. Our findings are also in agreement with those of Sumiya et al. (1982), who indicated that larger planting density stands exhibited increased wood densities and dynamic modulus of elasticity. Moreover, it was found that the Edu values were 9%–11% greater than the MOE values, while the MOE values were 6.5%–8.3% greater then the Edt values.

Zhang et al. (2002) indicated that the black spruce (*Picea mariana*) grown in narrowest spacing sites including the stand densities of 3086, 2500, and 2066 trees/ha have a comparable lumber strength and stiffness, while the wider spacing site of stand density of 1372 trees/ha has a significantly lower strength and stiffness.

Effects of lumber grades on mechanical properties

Table 3 shows the relationships between lumber grades, ρ_u, Vu, Edt, Edu, MOE, and MOR analyzed by using the multiple new-range Duncan test.

Wood density (ρ_u).—For lumber graded visually according to CNS14631 standard, no significant differences (0.05 level) in ρ_u values among grades A, B, and U were observed. However, significant differences between A and H (out-grade), and between grades B and H were found.

Ultrasonic velocity (Vu).—The Vu values of construction grade (A) lumber were significantly greater than those of the other graded lumber,

TABLE 3. *Analysis of multiple new-range Duncan's test of ρ_u, Edt, Edu, MOE and MOR for various lumber graded by CNS14631.*

Lumber grades	H	U	B	A
Average density (g/cm^3) (ρ_u)	0.407 a[1]	0.416 ab	0.421 b	0.422 b
Average Vu (m/s)	4965 a (332.2)	5003 a (308.6)	5075 a (335.7)	5255 b (335.9)
CV%	6.5	6.2	6.6	6.4
Average Edt (×10^3 MPa)	8.4 a (1.5)	8.7 a (1.5)	9.5 b (1.7)	10.0 b (1.7)
CV%	17.9	17.6	17.6	17.1
Average Edu (×10^3 MPa)	10.1 a (1.7)	10.5 a (1.7)	11.3 b (1.9)	11.7 b (2.0)
CV%	17.2	16.4	16.3	17.1
Average MOR (MPa)	46.2 a (11.2)	47.2 a (9.7)	48.8 a (9.1)	55.8 b (10.7)
CV%	24.1	20.6	18.8	19.1
Average MOE (×10^3 MPa)	9.2 a (1.7)	9.4 a (1.8)	9.9 a (1.9)	10.7 b (2.1)
CV%	18.3	19.0	18.8	19.9

Note: The values in parentheses represent standard deviations.
Lumber grades: A: construction grade, B: standard grade, U: utility grade, H: out grade.
(A) (B) (U) (H)
Number of specimens of different grades: A: 23, B: 47, U: 96, H: 64.
[1] Values sharing the same letter are not significantly different at the 0.05 level.

while no significant differences in Vu values among other graded lumbers were observed. The average Vu values of different graded lumbers in decreasing order were construction grade (A), > standard grade (B), > utility grade (U), > out grade (H).

Dynamic modulus of elasticity (Edu).—The Edu values of grades A and B lumbers were significantly greater than those of other graded lumbers, but significant differences (0.05 level) between grades A and B, and between grades U and H were not observed. This tendency is similar to the previous results on ultrasonic velocity (Wang and Lin 1996; Wang and Ko 1998).

Wang and Lin (1996) indicated that for the Japanese cedar lumber graded visually according to the JAS standard, the largest Edu value appeared in special graded lumber, followed by first-grade, second-grade, and third-grade. In this study as shown in Table 3, the average Edu values for lumber of different grades in decreasing order were construction grade > standard grade > utility grade > out-grade. The results are consistent with those previously reported (Wang and Lin 1996; Wang and Ko 1998).

Dynamic modulus of elasticity (Edt).—The Edt values of grades A and B lumber were significantly greater than those of grades U and H lumber, but no significant differences existed among the lumber of different grades.

Modulus of rupture (MOR).—The MOR values of A-graded lumber were significantly greater than those of other graded lumber (B, U, and H), but significant differences among grades B and U, and H were not observed.

Modulus of elasticity (MOE).—The MOE values of A-graded lumber were significantly greater than those of other graded lumber (B, U, and H), but significant differences among grades B, U, and H were not found.

The above-mentioned results reveal that the better graded lumber had higher MOR and MOE values. These results were consistent with the tendency of the relationships between lumber grades and Edu and Edt found in this study.

TABLE 4. *Coefficients of linear regression formulas for the correlation between mechanical properties and ultrasonic velocity.*

Items of strength	Items	Coefficients a	b	r	F
MOR	MOE	56.25	0.0044	0.794	410.9
MOR	Edu	8.54	0.0037	0.659	498.4
MOR	Edt	8.96	0.0044	0.692	212.5
MOR	Vu	−43.18	0.0181	0.582	119.8
MOE	Vu	−11984	4.232	0.763	340.5
MOE	Edt	937.47	0.971	0.856	646.0
MOE	Edu	841.12	0.820	0.815	190.3
Edt	Edu	273.93	0.809	0.913	1842.2
Edt	Vu	−12414	4.222	0.864	707.8
Edu	Vu	−14496	4.983	0.904	975.7

Notes: Linear regression formula: y = a + bx, y: values of MOR, MOE, Edt, Edu; x: MOE, Edu, Edt, Vu; a, b coefficients of linear regression formula.

Correlations between physical and mechanical properties

The correlation between ultrasonic velocity (Vu), dynamic modulus of elasticity (Edu, Edt), bending strength (MOR, MOE) of Taiwania could be represented by the positive linear regression formulas, summarized in Table 4 and Figs. 2–6. Although the correlation coefficients (r) were slightly lower, ranging from 0.582 to 0.913, there was a highly significant difference at 0.01 confidence level (**) as indicated by the F-test.

These results are in agreement with many previous works. The correlation coefficients (r) for the linear regression formula between E_D and MOE were 0.86 and 0.96 for Japanese cedar (*Cryptomeria japonica*) and China fir (*Cunninghamia lanceolata*), respectively, as reported by Lin et al. (1992). Tanaka (1988) also reported an r-value of 0.88–0.66 for Japanese cedar ob-

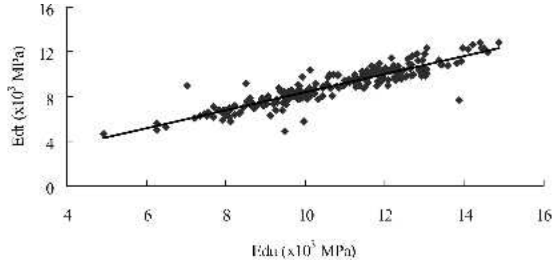

FIG. 2. Relationships between Edu and Edt.

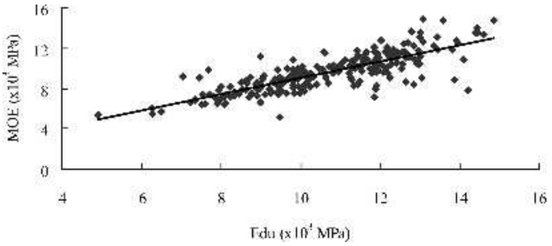

FIG. 3. Relationships between Edu and MOE.

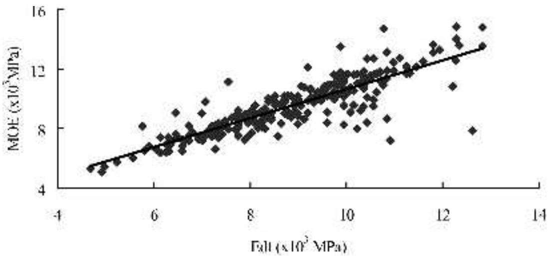

FIG. 4. Relationships between Edt and MOE.

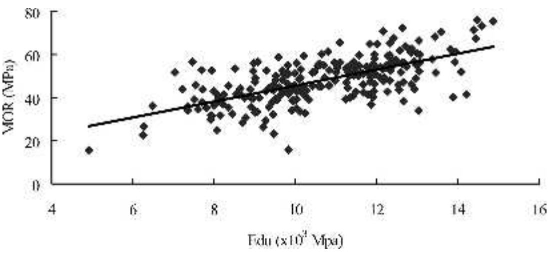

FIG. 5. Relationships between Edu and MOR.

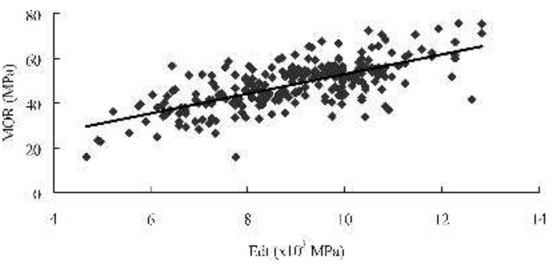

FIG. 6. Relationships between Edt and MOR.

tained by a nondestructive test. Wang and Lin (1996) had an r-value of 0.83 for Japanese cedar obtained by a Metriguand Model 340 Transverse Vibration Tester. Furthermore, Nagatomi et al. (1992) obtained an r-value of 0.75–0.97 for Japanese cedar using the longitudinal vibration method, and Sandoz (1989) obtained an r-value of 0.80 for spruce (*Picea spp.*) using the ultrasonic test. Wang and Ko (1998) obtained an r-value of 0.70–0.79 for Japanese cedar using the stress-wave timer test. However, the correlation coefficients (r) for the linear regression formula between MOR and MOE were 0.70–0.85 for Japanese cedar, and 0.73 for China fir obtained by the four-point bending test (Wang and Lin 1996; Wang and Ko 1998; Lin et al. 1992). Faust et al. (1990) reported an r-value of 0.732–0.752 for actual dimensions of two hardwood beams obtained by the four-point bending test. Zhou and Smith (1991) obtained an r-value of 0.72 for white spruce (*Picea spp.*), and Tanaka (1998) reported an r-value of 0.58–0.72 for Japanese cedar obtained by the four-point bending test.

The average values of these three nondestructive tests showed a decreasing order as follows: Edu > MOE > Edt. The Edu values were 9.5%–14.0%, and 17.0%–22.0% greater than the MOE and Edt values, respectively; while the MOE values were 5.2%–8.8% greater than the Edt values.

CONCLUSIONS

(1) Lumber obtained from the site with type S planting density (6840 trees/ha) was mostly of better grade (84.6% including construction and standard grades), followed by type Q (69.1%), type R (62.5%), whereas poorer lumber was found mostly from trees with type P planting density (1000 trees/ha) (41.6%).
(2) Specimens cut from trees of type S planting density (6940 trees/ha) site had the largest average Vu, Edt, Edu, MOE, and MOR values, followed in decreasing order by those of type P, type R, and type Q sites.
(3) The average Vu, Edt, Edu, MOE, and MOR values of visually graded construction grade lumber were significantly greater than those of standard utility and out-grades.
(4) The average Edu values were 9.5%–14.0% and 17.0%–22.0% greater than the MOE and Edt values, respectively.

(5) Interrelations between Vu, Edu, Edt, MOE, and MOR can be represented by positive linear regression formulas. The differences were significant.
(6) The mechanical properties are not related to wood density.

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