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Dynamic modulus of elasticity and bending properties of young Taiwania trees grown with different thinning and pruning treatments

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Abstract The effects of different thinning and pruning methods on the bending strength and dynamic modulus of elasticity (DMOE) of young Taiwania (*Taiwania cryptomerioides* Hay) were investigated. The average DMOE, modulus of elasticity (MOE), and modulus of rupture (MOR) in the thinning treatments showed the following trend: no thinning > medium thinning > heavy thinning. This indicates that thinning reduces average bending properties. The average DMOE, MOE, and MOR in the pruning treatments showed the following trend: medium pruning > no pruning > heavy pruning. According to this tendency, better average qualities of lumber and specimens were from wood subjected to no-thinning and medium-pruning treatments according to an ultrasonic wave technique and static bending tests. However, most results showed no statistically significant differences among thinning, pruning, and thinning and pruning treatments. The average values of DMOE, MOE, and MOR of visually graded construction-grade lumber were significantly greater than those of below-grade lumber. Moreover, there were very significant positive relationships between density, ultrasonic velocity, DMOE, MOE, and MOR, although the determination coefficients were small.

Key words Thinning · Pruning · Ultrasonic wave · Bending strength · Dynamic elasticity · Taiwania

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Introduction

It is generally recognized that the properties of wood are affected by genetic factors of the trees, environmental conditions of the site, silvicultural practices, and others. In general, tree growth can be directly controlled by plantation techniques, including thinning and pruning, which are two important practices for commercial plantation wood. Thinning treatment helps to increase volume growth, while pruning treatment helps to improve lumber quality. However, some investigators have found that wood properties are changed as a result of silvicultural manipulations.[1]

The dynamic modulus of elasticity (DMOE), modulus of elasticity (MOE), and modulus of rupture (MOR) are the most common properties used to indicate the quality of wood used for construction. They are very important factors in determining the strength of wood, apart from consideration of specific end uses.

In a series of investigations on the wood quality of Taiwania trees grown with different thinning and pruning treatments, it was previously reported that thinning caused wider annual rings than medium thinning and no thinning, pruning caused narrower annual rings than no pruning, and that the average ring density in the thinning treatments showed a trend as follows: no thinning > medium thinning > heavy thinning.[2] The average ring density in the pruning treatments showed a trend as follows: medium pruning > no pruning > heavy pruning. However, no statistically significant differences existed between thinning and no thinning.[2] Also, it was reported that heavy thinning caused more knots and larger-diameter knots than medium or no thinning; moreover, pruning caused fewer knots and smaller-diameter knots than no pruning.[3] However, there has been little investigation concerning the effects of thinning and pruning practices on the wood quality and strength properties as indicated by the bending test.

To increase our knowledge about the influence of silvicultural treatment on the bending properties of lumber and wood for the wood products industry, this study investigated the effects of thinning and pruning treatments on the

DMOE, MOE, and MOR of Taiwania by the ultrasonic-wave method and the static bending test. The interrelationships between lumber grades and strength properties were also examined. The results provide basic information for future management practice and wood utilization of Taiwania.

Material and methods

Testing materials

The study site was located in the No. 12, Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaohsiung County, Taiwan, ROC. The area of the study site was about 2 ha, and was divided into 27 smaller plots each of 0.04 ha in area, including a buffer zone. The three thinning treatments were heavy thinning [basal area 28 m^2/ha at diameter breast height (DBH)], medium thinning (33 m^2/ha), and no thinning (42 m^2/ha). Heavy thinning and medium thinning harvested stocks from the original 42 m^2/ha to retain 28 m^2/ha and 33 m^2/ha, respectively. The three pruning treatments were heavy pruning (4.5 m), medium pruning (3.6 m), and no pruning. Heavy pruning and medium pruning are defined as pruning from the root base upward to 4.5 m and 3.6 m of the tree height, respectively. The study plantation was planted at a density of 1750 trees/ha in 1980. Thinning and pruning treatments were implemented in 1990.

The three levels of thinning were combined with the three levels of pruning treatment. Therefore, nine silvicultural practices (three thinning × three pruning treatments) were used in this study. Each combination of thinning and pruning was performed in triplicate, so a total of 27 sample plots were used.

Experimental method

The diameter and height of each tree on all 27 plots were measured. The average DBH values and tree heights are shown in Table 1.[2] A mean diameter from the trees was selected from each plot, and a total of 27 sample trees were cut. These trees were harvested on February 14–15, 2001, when they were about 20 years old.

Each sample tree was cut into logs at 2.2-m intervals from the DBH position to the top and a 1.3-m log from the base to the DBH. The longer logs were band-sawn into lumber according to the cant sawing method, as shown in Fig. 1. All lumber was 2.2 m long with nominal width by thickness dimensions of 8.9 × 3.8 cm. For the shorter logs small clear specimens [24 (long) × 1.5 (width) × 1.5 cm (thickness)] were cut from 1.3 m logs approximately at the positions of its DBH in the same direction.

The lumber was assessed in accordance with the grades of structural sawn lumber of CNS14631 (CNS, 2002). Sawn lumber was classed into "construction," "standard," "utility," and "below grade." After the lumber samples were visually graded according to the CNS rules, their moisture content and wood densities in air-dried condition were measured. The lumber and specimens were also analyzed using an ultrasonic wave technique for longitudinal transmission; the ultrasonic wave apparatus (Sylvatest, frequency 16 kHz; Swiss Products) used transmitting and receiving transducers.

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

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

$$\mathrm{DMOE} = V^2\rho \tag{2}$$

where V is the ultrasonic wave velocity in the direction parallel to the grain of lumber and specimen, L is the distance between the two transducers, T is the propagation time of the pulse from the transmitting transducer to the receiving transducer, DMOE is in the direction parallel to

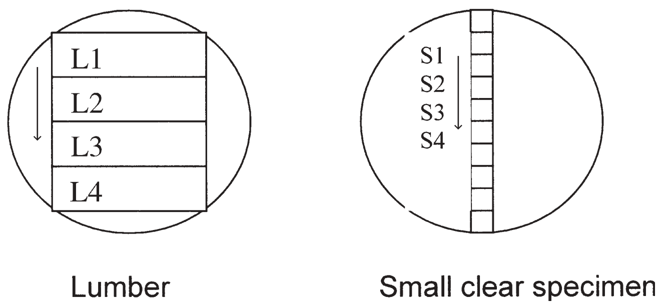

Fig. 1. Notation for log beams cut from one side to another. *L1* to *L4*, large beam specimens; *S1*, *S2*, *S3*, *S4*, . . . , small clear specimens

Table 1. Structure of different thinning treatments of Taiwania stands

Treatment	Phase	Age (years)	Density (trees/ha)	Mean DBH (cm)	Mean height (m)	Basal area (m^2/ha)	Volume (m^3/ha)
Heavy thinning (27.5 m^2/ha)	Before thinning	11	1750	17.13	9.85	42.42	197.38
	After thinning	11	929	19.69	10.41	27.60	131.65
	After 9 years	20	811	28.03	15.21	50.04	342.53
Medium thinning (32.5 m^2/ha)	Before thinning	11	1689	17.39	9.93	42.17	197.00
	After thinning	11	1135	19.14	10.32	32.52	154.45
	After 9 years	20	1097	26.56	15.80	60.78	432.14
No thinning (42 m^2/ha)	–	11	1801	16.89	9.81	41.95	195.47
	–	20	1528	23.53	15.50	66.44	463.45

DBH, diameter at breast height

Table 2. Bending properties of lumber obtained from different thinning and pruning regimes

Parameter	Treatment		
	Heavy	Medium	None
Density (kg/m^3)			
Thinning	403*	421	427*
Pruning	404	421	426
V (m/s)			
Thinning	4391*	4417**	4577*,**
Pruning	4481	4480	4423
DMOE (MPa)			
Thinning	8130*	8599	9322*
Pruning	8471	8857	8722
MOE (MPa)			
Thinning	6878*	7218	7852*
Pruning	7158	7708	7183
MOR (MPa)			
Thinning	38.3	41.0	41.8
Pruning	38.8	41.9	40.3

DMOE, dynamic modulus of elasticity; MOE, modulus of elasticity; MOR, modulus of rupture
* and** $P < 0.05$ by Duncan's multiple range test within the same row

Table 3. Bending properties of specimens obtained from different thinning and pruning regimes

Parameter	Treatment		
	Heavy	Medium	None
Density (kg/m^3)			
Thinning	393	401	413
Pruning	391	412	405
V (m/s)			
Thinning	5421	5372	5418
Pruning	5208	5594	5410
DMOE (MPa)			
Thinning	12158	12240	12852
Pruning	11191*	13635*	12424*,**
MOE (MPa)			
Thinning	4802	4694	4896
Pruning	4256*	5486*,**	4650**
MOR (MPa)			
Thinning	56.7	59.0	59.8
Pruning	54.0*	62.9**	58.5*,**

* and** $P < 0.05$ by Duncan's multiple range test within the same row

the grain of lumber and specimen, and ρ is the air-dried density of lumber and specimen.

The static bending tests were conducted in accordance with the third-point loading method for lumber and center loading method for specimen, using a Shimadzu UH-10A universal-type testing machine. All the specimens were located flat direction (wise loading) for the bending tests. The span was 150 cm, the distance between the two loading points was 50 cm for lumber, and the span was 28 cm for specimens. The proportional limit, ultimate load, and deflection were obtained from load-deflection curves, and the MOE and the MOR were calculated.

Results and discussion

Effects of thinning and pruning on wood density

The differences in air-dried wood density among the lumber and specimens cut from trees of different thinning and pruning levels were analyzed using the ANOVA analysis of variance and multiple new-range Duncan's test. The results are shown in Tables 2 and 3. The average air-dried densities of lumber and specimens from the thinning treatments showed the following trend: no thinning > medium thinning > heavy thinning. In addition, the average densities from the pruning treatments showed the following trend: no pruning > medium pruning > heavy pruning for lumber and medium pruning > no pruning > heavy pruning for specimens. However, no significant differences were shown for density among the three pruning treatments for lumber and specimens and thinning treatments of specimens. These results are similar to those previously reported by Wang et al.,[2] who indicated that this tendency may be attributed to the fact that trees grown at relatively wide spacings have wider ring widths and lower density.

Wang and Chen[4] indicated that Japanese cedar trees grown at relatively wide spacing had wider annual ring widths. Koga et al.[5] reported that trees from thinned plots showed a significant increase in annual ring widths after thinning. Moreover, Wang et al.[2] stated that there were very significant negative relationships between the average ring width and the various wood densities in annual rings for Taiwania, but the determination coefficients were very small. This indicated that with the wider annual ring widths, there was lower wood density in the annual rings. On the contrary, with the narrower annual ring widths, the wood density in the annual rings was higher.

In addition, some studies have reported that thinning causes a slight decrease in wood density for *Pinus radiata* and *Pesudotsuga menziesii*.[6–8] However, others have indicated that thinning had no effect or minor effects on wood density of *Pinus pinaster*, *Pinus radiata*, *Pinus taeda*, and *Larix leptalepis*.[9–12] Similar results have been reported on the earlywood and latewood density of Douglas fir.[13] In that study, no-thinning treatment not only yielded higher ring density, earlywood density, and latewood density, but also caused greater variation. This showed a contrary trend with the differences in annual ring width among different thinning treatments. From this result, it can be seen that heavy thinning will reduce the average values of air-dried density within the annual rings.

Zobel and van Buijtenen[1] also indicated that the effects on ring density in some species increase with pruning, because pruning apparently causes an early cessation of juvenile wood formation, an increase in latewood, and an increase in tracheid length. That study also noted that pruning had no effect on the specific gravity of *Eucalyptus grandis*.

In the current study, the average air-dried density of the lumber was higher than that of the specimens, because the specimens were clear and the lumber contained high-density knots. The density of lumber and specimens were influenced by the defects (knots), ring traits (width), and anatomic characteristics (tissue), etc. We consider that knot traits and juvenile wood are the most important factors affecting variation in wood properties.

Effects of thinning and pruning on mechanical properties

Dynamic modulus of elasticity and modulus of elasticity by static bending

A comparison of average DMOE values of Taiwania plantation lumber and specimens treated with different thinning and pruning regimes is shown in Tables 2 and 3. The variations of DMOE in the thinning treatments for lumber and specimens showed the following trend: no thinning > medium thinning > heavy thinning. It was also found that the DMOE in the pruning treatments for lumber and specimens were in the following decreasing order: medium pruning > no pruning > heavy pruning. According to the results of statistical analysis shown in Tables 2 and 3, significant differences ($P < 0.05$) existed for the DMOE of lumber between heavy and no thinning treatments. However, no significant differences existed for other thinning and pruning treatments. This is similar to the results of Wang et al.,[3] who indicated that heavy thinning caused more knots and large-diameter knots than medium or no thinning.

The average MOE values for lumber cut from trees with different thinning treatments decreased in the following order: no thinning > medium thinning > heavy thinning for lumber and no thinning > heavy thinning > medium thinning for specimens. The variations of MOE values in the pruning treatments for lumber and specimens showed the following trend: medium pruning > no pruning > heavy pruning. The results of static testing showed that lumber that was not thinned had significantly larger MOE values than lumber from heavy thinning; and specimens from medium pruning had significantly larger MOE values than those from heavy pruning and no pruning. There were no significant differences among lumber and specimens from the other silvicultural treatments. These tendencies in the results indicate that no thinning and medium pruning treatments produced higher MOE values for lumber and specimens than other treatments.

Modulus of rupture by static bending

The effects of thinning, pruning, and the thinning and pruning interaction on MOR were not significant by ANOVA, except that specimens from heavy pruning and medium pruning had a significantly larger MOR than others. The comparison of MOR values for different thinning and pruning regimes is shown in Tables 2 and 3. The variations of MOR in the thinning treatments showed the following trend: no thinning (41.8 MPa) > medium thinning (41.0 MPa) > heavy thinning (38.3 MPa) for lumber and no thinning (59.8 MPa) > medium thinning (59.0 MPa) > heavy thinning (56.7 MPa) for specimens. This tendency indicates that heavy thinning produced smaller MOR values than medium and no thinning treatments. The variations of MOR in the pruning treatments showed the following trend: medium pruning (41.9 MPa) > no pruning (40.3 MPa) > heavy pruning (38.8 MPa) for lumber and medium pruning (62.9 MPa) > no pruning (58.5 MPa) > heavy pruning (54.0 MPa) for specimens. This tendency indicates that medium pruning produced larger MOR values than heavy and no thinning treatments.

The MOR of lumber and specimens are influenced by the defects (knots), ring traits (width), anatomic characteristics (tissue), etc. We believe that knot traits and juvenile wood character (e.g., tracheid length, microfibril angle) of this study are important factors that effect the variation in wood properties. Wang et al.[3] indicated that heavy thinning caused more knots and larger-diameter knots than medium thinning or no thinning; moreover, pruning caused fewer knots and smaller-diameter knots than no pruning, although the results also showed that the healing process seemed to have produced not completely clear wood. Wang and Chen[4] indicated that the boundary between juvenile and mature wood was between about the 17th and 22nd annual rings from the pith for Japanese cedar. The lumber and specimens of this study may not yet be considered mature wood because Lin et al.[14] indicated that the juvenile wood region of Taiwania was around 10–15 cm away from the pith by segmented regression analysis for crushing strength parallel to grain and was about 18–23 years old. Thus, the MOR of lumber and specimens may have been influenced by the characteristics of juvenile wood. Wang and Chiu[15] reported that juvenile wood has substantially less mechanical strength compared with mature wood of the same specific gravity. Zobel and Sprague[16] indicated that differences in characteristics between juvenile and mature wood are well known in the conifers, e.g., specific gravity, mechanical properties, moisture content, cell traits, chemical characteristics, amount of variation, etc. Furthermore, the MOR of specimens was higher than in the lumber, because the lumber contained high-density knots and other defects.

Effects of lumber grades on mechanical properties

Relationships among lumber grade, DMOE, MOE, and MOR as analyzed using statistical tests are shown in Table 4. According to the results of a multiple new-range Duncan test ($P < 0.05$), there were significant differences of DMOE, MOE, and MOR between construction grade and below grade. However, there were no significant differences for these indices among the other grades.

The variations of DMOE, MOE, and MOR in the different lumber grades showed the following trend: construction > standard > utility > below grade. This tendency indicates that the construction grade has higher mechanical properties (DMOE, MOE, and MOR) than other grades. However, no significant differences of DMOE, MOE, and MOR among construction, standard, and utility grades were ob-

Table 4. Analysis of multiple new-range Duncan test of bending properties for the four different lumber grades

	Lumber grade			
	Below grade	Utility	Standard	Construction
Density (kg/m^3)	383*	418*,**	422*,**	411
V (m/s)	4154*	4177**	4331	4558***
DMOE (MPa)	6904*	7679	8373	8972*
MOE (MPa)	5691*	6325	6846	7527*
MOR (MPa)	30.4*,**	35.0	38.0*	42.0**

* and** $P < 0.05$ by Duncan's multiple range test within the same row

Table 5. Coefficients of linear regression formulas ($Y = AX + B$) for the correlation among mechanical properties and ultrasonic wave speed

Coefficients					R^2	F value
	Y	X	A	B		
Lumber	MOR	ρ	1180	−92	0.24	87**
	MOR	V	0.14	−226	0.40	185**
	MOR	DMOE	0.003	124	0.47	248**
	MOR	MOE	0.004	119	0.60	429**
	MOE	V	36	−89080	0.66	549**
Specimen	MOR	ρ	923	202	0.18	48**
	MOR	V	0.09	88	0.36	123**
	MOR	DMOE	0.002	318	0.52	228**
	MOR	MOE	0.006	311	0.62	350**
	MOE	V	18	−47666	0.70	494**

R^2, coefficient of determination; ρ, density; V, ultrasonic wave velocity
* $P < 0.05$; ** $P < 0.01$

served. This might be because these three grades are based solely on the maximum knot diameter ratio but ignore the quality of knots and other factors. For example, the ring width and juvenile tissue might be considered two important factors for lumber. However, this result is consistent with the findings reported by Wang and Lin,[17] who indicated that significant differences between strength values and lumber grades did not exist. They also stated that the knot diameter ratio showed negative regressions as related to DMOE, MOE, and MOR. Thus, the maximum knot diameter ratio of lumber may be used both as an index function for mechanical properties and for visual assessment of lumber grades. Relationships among lumber density analyzed by using statistical test are shown in Table 4. According to the results of a multiple new-range Duncan test ($P < 0.05$), there were significant differences between standard, utility grade, and below grade, but there was no significant difference observed among other grades.

Effect of wood density on mechanical properties

The values of MOR for Taiwania increased with increased wood density, and the relationship could be represented by positive linear regression formulas (Table 5). The results are similar to those reported earlier by Wang and Lin,[17] Wang and Ko,[18] and Lin et al.[19] that were obtained from small diameter logs of Japanese cedar and China fir. Those previous studies suggested that the effect of wood density of plantation lumber on its strength might be negligible because it has high juvenile wood content, poor branch knot performance, and/or seriously irregular grain at the knots. Furthermore, Lin et al.[19] indicated that the specific gravity of Japanese cedar and China fir increased with increases in the percentage of knots in a specimen. In other words, the effects of defects (e.g., knots and anatomic traits) on mechanical properties are more significant than density.

Based on Eqs. 1 and 2, there is a positive correlation between DMOE and density (ρ). However, Mishiro[20] reported that Young's modulus in the longitudinal direction generally tended to increase with increased density, and also indicated that Young's modulus was independent of the density for softwood specimens. In addition, Li[21] reported that there was no significant relationship between the Young's modulus in the longitudinal direction and specific gravity, and indicated by an ultrasonic-wave test that there is another important factor which affects mechanical properties. Although the density is an important parameter to define the dynamic force, the effect of density on DMOE may be caused by wood anatomic traits, e.g., microfibrillar angle and tracheid length. Furthermore, these results are limited to juvenile wood. Therefore, there is some reason to believe that some of the results may be due to the properties of juvenile wood and knots.

Correlations among the three mechanical properties

The correlations among three mechanical properties (DMOE, MOE, and MOR) of Taiwania lumber and specimens could be represented by positive linear regression formulas (Table 5). The determination coefficients (R^2) were highly significant at the 0.01 level, as indicated by the F value test. These results are in agreement with many previous studies.[17–19]

Based on the above analyses and results, some of the variation in results may be due to juvenile wood, cell types, and levels of chemical components that have various degrees of impact on the ultrasonic properties of wood. Juvenile wood can be characterized by short tracheid length, thin cell walls in latewood, low degree of cellulose crystallinity, and large microfibril angle in the tracheids. Wang and Chiu[15] indicated that the five anatomical and physical properties that affect strength properties are specific gravity, ring width, microfibril angle, degree of crystallinity, and tracheid length.

Using the ultrasonic method, Tanaka[22] reported that the correlation coefficient for the linear regression formula between the propagation velocity of ultrasonic waves and MOE was only 0.35. Therefore the density of specimens cannot be ignored when calculating the MOE value. Nanami et al.[23] studied the regressions between the values of the square of stress transmission velocity and DMOE, finding that the correlation coefficients were high for wood from each forest site. Wang and Ko[18] reported that the relations among the squared value of stress wave transmission velocity and DMOE, MOE, and MOR, can be represented by positive linear regression formulas with highly significant differences for regression. They also suggested that the transmission wave velocity might be used as an indicator to assess the quality of timber.

Conclusions

The effects of different thinning and pruning methods on the bending properties of young Taiwania trees were investigated, with the following results:

1. Average air-dried density of lumber and specimens showed a trend as follows: no thinning > medium thinning > heavy thinning for thinning treatments and no pruning or medium pruning > heavy pruning for pruning treatments.
2. Magnitude of DMOE, MOE, and MOR showed the following trend: no thinning > medium thinning > heavy thinning for thinning treatments and medium pruning > no pruning > heavy pruning for pruning treatments.
3. Average values of DMOE, MOE, and MOR of visually graded construction grade lumber were significantly greater than those of below grade groups.
4. The values of DMOE, MOE, and MOR increased with increases of the wood density. Interrelations among DMOE, MOE, and MOR can be represented by positive linear regression formulas. The differences were highly significant.

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