EVALUATION OF WOOD QUALITY OF TAIWANIA TREES GROWN WITH DIFFERENT THINNING AND PRUNING TREATMENTS USING ULTRASONIC-WAVE TESTING

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ABSTRACT

The effects of different thinning and pruning methods on the wood quality of Taiwania (*Taiwania cryptomerioides* Hay.) trees and specimens using ultrasonic-wave method were investigated. Thinning resulted in lower ultrasonic-wave velocity (Vtree), dynamic modulus of elasticity (MOEtree) of standing trees, ultrasonic-wave velocity (Vlumber), and dynamic modulus of elasticity (MOElumber) of specimens than non-thinning, and the medium pruning had higher Vtree, Vlumber, MOEtree, and MOElumber than non-pruning. The higher structural properties of Taiwan trees and specimens occurred in the non-thinning and medium pruning treatment by ultrasonic-wave technique.

The variations of Vtree, Vlumber, MOEtree, and MOElumber in the thinning and pruning treatments showed the similar trend. Results of this study also demonstrate that the effect of silvicultural practices on wood properties can be identified with the ultrasonic-wave properties of trees. This indicates that this non-destructive ultrasonic-wave technique can be provided basic information for future management practice and wood utilization of Taiwania.

Keywords: Taiwania, ultrasonic-wave technique, thinning, pruning, ultrasonic wave velocity, dynamic modulus of elasticity.

INTRODUCTION

It is important to increase our knowledge about the influence of silvicultural treatments on the quality of standing trees and wood obtained from them. Silvicultural manipulation can either alter wood directly through physiological changes within the tree, or it can change the tree form, which in turn may have an effect on wood properties. Two important practices for commercial plantations include thinning and pruning. Thinning helps increase volume growth and pruning helps improve the quality of lumber obtained from a given trees. In some studies, silvicultural practices applied to plantations improved tree growth and form without ad-

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versely affecting wood properties. However, some investigators found that wood properties are changed as a result of silvicultural manipulations (Zobel and van Buijtenen 1989).

One nondestructive tool that has been applied to trees, logs, sawn-timbers, and wood-based materials to estimate their physical properties utilizes ultrasonically induced waves. The applicability of this tool for assessing the quality of wood materials has been investigated extensively. Currently, there is strong interest in developing and using cost-effective technologies to evaluate wood quality in standing trees. In particular, several studies have shown a good relationship between the dynamic modulus of elasticity of standing trees obtained using impact and ultrasonically induced stress waves and the static modulus of elasticity of lumber cut from standing trees (Wang et al. 2001; Chuang and Wang 2001; Ikeda and Kino 2000; Ikeda and Arima 2000; Ikeda et al. 2000a; 2000b; Nakamura 1996; Nanami et al. 1992a; 1992b; 1993). These encouraging results led us to hypothesize that the use of their nondestructive technique may be useful in assessing the effect of thinning and pruning on wood quality in standing trees.

The primary objective of the study reported was to investigate the effects of thinning and pruning treatment on the dynamic modulus of elasticity of standing trees and lumber of Taiwania. A secondary objective was to detect whether the effect of silvicultural practices on wood quality of Taiwania could be identified using this technique.

MATERIALS AND METHODS

The trees used in this study were located on a site at an elevation of 1600 m in compartment No12, Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaohsiung Country, Taiwan, R.O.C.. The mean annual temperature, relative humidity, and precipitation from 1986 to 1993 were 18.6°C, 81%, and 2,280 mm, respectively. About 88% of the rainfall occurred during the time period from April to September during any given year.

The site was about 2.0 ha, and it was divided into 27 smaller plots, of 0.04 ha each in area including buffer zones. The study plantation was planted at a rate of 1750 trees/ha in 1980. Thinning and pruning treatments were implemented in 1990. Three levels of thinning included heavy thinning (28 m^2/ha), medium thinning (33 m^2/ha), and non-thinning (42 m^2/ha). The heavy and medium thinning harvested stocks from the original 42 (m^2/ha) to retain 28 (m^2/ha) and 33 (m^2/ha), respectively. Three pruning levels were heavy pruning (4.5 m), medium pruning (3.6 m), and non-pruning. The heavy and medium pruning treatments represented trees that were pruned from the root base upward to 4.5 m and 3.6 m of the tree height, respectively.

Three levels of thinning were combined with another three levels of pruning treatment. Therefore, nine silvicultural practices (3 thinning × 3 pruning treatments) were used in this study. The same thinning and pruning treatment plot was repeated three times. So, in total, 27 sample plots were designed. The structures of different thinning treatments of Taiwania stands are shown in Table 1.

The diameter and height of each tree on the 27 small plots were measured. Average diameter breast height (DBH) and tree heights are shown in Table 1. A mean diameter from the trees was selected from each plot, and 27 sample trees in total were sampled. A commercially available ultrasonic testing tool was used to evaluate the trees (Fig. 1). After field tests, 27 trees, one in each plot, were felled. A 50-m-long bole section was cut from each felled tree. The sections were then cut into lumber (pass through pith) in the same direction. Thus, all the pieces of lumber were 50 cm long (dimension: 50 cm (long) × DBH cm (wide) × 5 cm (thick)) and were cut from 50-cm bole sections. The lumber specimens were also tested nondestructively. The transmitting and receiving transducers (*awl* type) were placed facing each other with the lumbers placed in between, and one by one every ring was tested for longitudinal direction. The specimens were taken to determine the green moisture content and the bulk density. The moisture contents of sample trees were determined using the oven-dried method.

The ultrasonic-wave velocity (Vtrees, Vlumber) and the dynamic modulus of elasticity

TABLE 1. *Structure of different thinning treatments of Taiwania stands.*

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

(MOEtrees, MOElumber) were calculated from the following formulas.

$$\text{Vtrees or Vlumber} = L/T \text{ (m/s)} \quad (1)$$

$$\text{MOEtrees} = \text{Vtrees}^2 \times \rho\text{eff}/g \text{ (kgf/cm}^2) \quad (2)$$

$$\text{MOElumber} = \text{Vlumber}^2 \times \rho/g \text{ (kgf/cm}^2) \quad (3)$$

where Vtrees and Vlumber are the ultrasonic-wave velocities in the direction parallel to the grain of trees and lumber, respectively; L is the distance between the two transducers; T is the propagation time of the pulse from the transmitting transducer to the receiving transducer; MOEtrees and MOElumber are the dynamic modulus of elasticity in the direction parallel to the grain of trees and lumber, respectively; ρeff is the effective density of wood in the sample tree; ρ is the air-dried density of wood in the lumber sample; and g is the gravitational constant.

The effective density (ρeff) suggested by Sobue (1993) was 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 ρeff was derived by multiplying K by ρ. A K value of 0.58 was used for the ultrasonic wave, as obtained in the author's previous report (Wang et al, 2002).

In this study, an analysis of variance (multifactor ANOVA) was used to determine if the thinning and pruning levels significantly affected green moisture content, ultrasonic-wave velocity, and dynamic modulus of elasticity. STATGRAPH software program was used. F values were computed to test for the significance of treatment. Where treatment effects were significant, means were compared using Duncan's multiple range test (STSC 1986).

RESULTS AND DISCUSSION

Physical characteristics

A series of investigations on the wood quality of Taiwania trees grown with different thinning and pruning treatments were evaluated (Chiu et al. 2002; Lin et al. 2002). The average diameter at breast height (DBH) of test sampled trees ranged from 23.53 cm to 28.03 cm. The average tree heights varied from 15.21 m to 15.80 m. The DBH and height growth of individual trees had significantly increased by intermediate and heavy thinning treatments. The different pruning treatments did not affect the increased DBH height. Based on the physical measurements on bole sections cut from trees, Taiwania had an average air-dried density range of 0.354 to 0.420 g/cm^3. The heavy thinning caused lower air-dried density than medium and non-thinning, medium pruning caused higher air-dried density than non-pruning and heavy pruning. Thus, the thinning treatment affected air-dried density more effectively than the pruning treatment.

The relation between the DBH and the bulk density of sample trees was examined. It is clear that the bulk density values decreased linearly with increasing DBH, and the relation could be expressed by the following linear regression.

Bulk density = – 0.0039DBH + 0.4471, R^2 = 0.33 F=12.4**

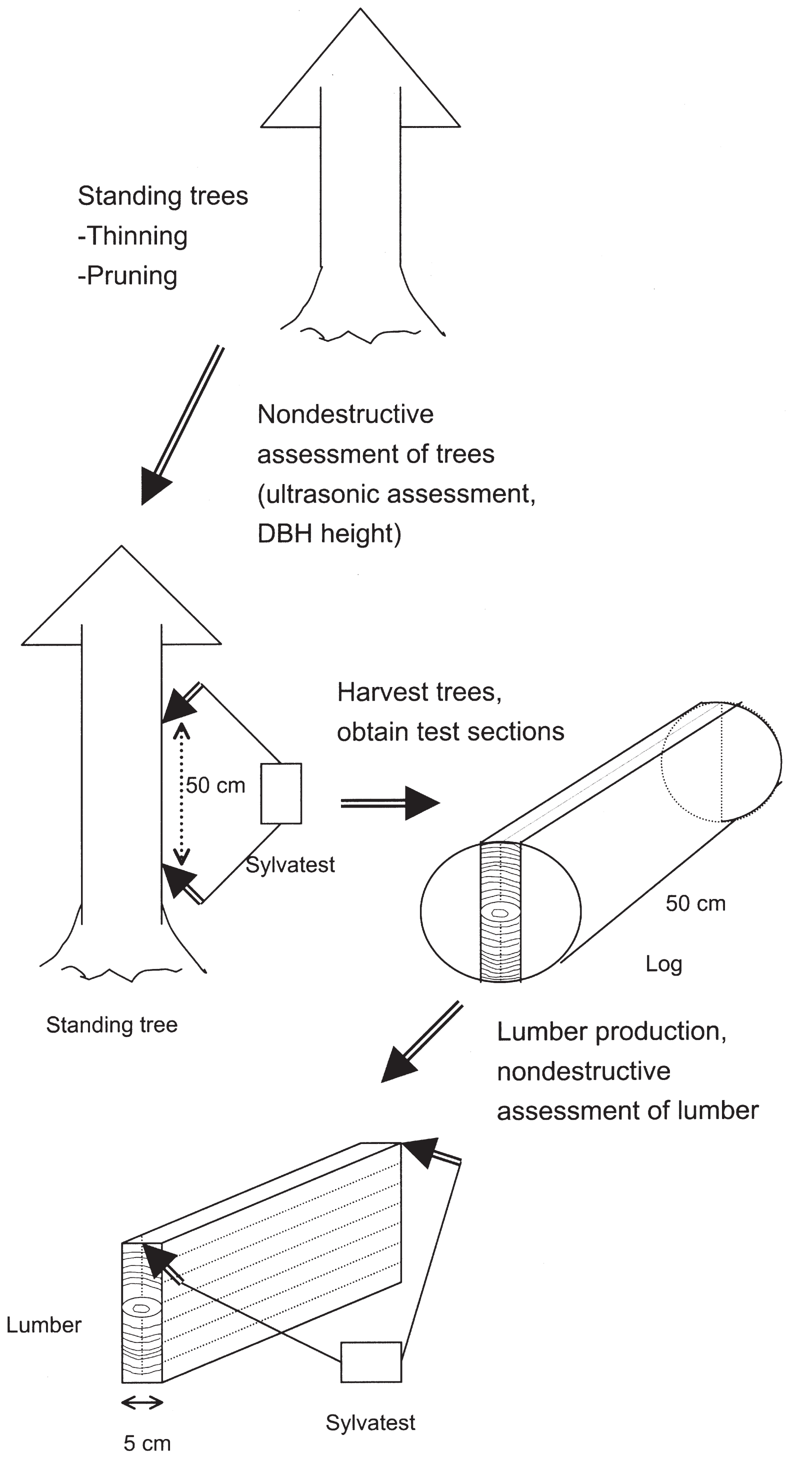

FIG. 1. Flow chart indicating the process of this study.

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, so they had a lower bulk densities. This finding was similar to that in Chuang and Wang's (2001) report.

Moisture content in green condition

The green moisture content (MC) of Taiwania sample was measured by the oven-dry method. These were analyzed using ANOVA, and the results are shown that the effects of thinning treatment and thinning by pruning interaction on the MC were significant. However, the green moisture content was not statistically affected by the pruning treatment.

The comparison of average MC of Taiwania plantation trees treated with different thinning, pruning, and thinning by pruning interaction regimes is shown in Table 2. The variations of MC in the thinning treatments showed the following trend: heavy (180.3%) > medium (177.3%) > non-thinning (153.1%). This indicates that the heavy thinning had higher MC than medium and non-thinning. The variations of MC in the pruning treatments showed the following trend: non-pruning (173.6%) > medium (169.5%) > heavy (167.6%). From this result, it can be seen that the pruning treatments will cause lower MC than that of non-pruning treatment. However, there was no significant difference in MC among these pruning treatments. The variations of MC in the thinning by pruning interaction treatments showed the following trend: BA (200.1%) × AC (196.3%) AB (186.2%) × BC (169.6%) × BB (162.2%) × CB (160.0%) × AA (158.3%) × CC(154.9%) × CA(144.5%). The results showed that the MC of individual tree was mainly significantly increased by thinning but not by pruning. Wang et al. (2003) indicated that the Taiwania trees grown at relatively wide spacing had wider annual ring widths and thinning reduces the average density in annual ring. In other words, trees from thinned plots showed a significant increase in annual-ring width. The large DBH and wide annual rings had lower densities so they had higher MC in even-age stands. Furthermore, the variation in average ring density after the pruning treatments showed a trend as follows: medium > no > heavy pruning (Wang et al.

TABLE 2. *Comparison of moisture content of Taiwania standing trees treated with different thinning and pruning regimes.* [1)]

(%)

Treatment / Moisture content	Heavy	Medium	Non
Thinning	180.3^{a} [2)]	177.3^{a}	153.1^{b}
	(22.6) [3)]	(19.8)	(23.2)
Pruning	167.6^{a}	169.5^{a}	173.6^{a}
	(32.9)	(19.2)	(21.6)

T × P	CA [4)]	CC	AA	CB	BB	BC	AB	AC	BA
	144.5^{a}	154.9^{ab}	158.3^{ab}	160.0^{ab}	162.2^{abc}	169.6^{abcd}	186.2^{bcd}	196.3^{cd}	200.1^{d}
	(40.4)	(15.5)	(10.2)	(9.3)	(6.8)	(15.3)	(26.7)	(7.9)	(8.6)

[1)] Measurements performed on February 14–15, 2001
[2)] Means within a given row with the same letter are not significantly ($p<=0.05$) different as determined by Duncan's multiple range test.
[3)] The values in parentheses represent the standard deviation.
[4)] Legend:
AA: Heavy thinning and heavy pruning treatments.
AB: Heavy thinning and medium pruning treatments.
AC: Heavy thinning and no pruning treatments.
BA: Medium thinning and heavy pruning treatments.
BB: Medium thinning and medium pruning treatments.
BC: Medium thinning and no pruning treatments.
CA: No thinning and heavy pruning treatments.
CB: No thinning and medium pruning treatments.
CC: No thinning and no pruning treatments.

2003). The higher density occurred in the medium (appropriate measure) pruning treatment so they had lower MC.

ULTRASONIC-WAVE PROPERTIES OF STANDING TREES

The dynamic modulus of elasticity (MOEtrees) for the trunks of standing Taiwania trees was calculated by adjusting the effective mobility of free water and effective density in the trunk at various moisture contents.

These were analyzed using ANOVA, and the results are shown that the MOEtrees and Vtrees were significantly influenced by the thinning and pruning treatment. However, it is also clear that the effects of thinning by pruning interaction on the MOEtrees and Vtrees were not significant. Therefore, the effects of thinning by pruning interaction were not analyzed any further.

The comparison of Vtrees of Taiwania plantation trees treated with different thinning regimes is shown in Table 3. The variations of Vtrees in the thinning treatments showed the following trend: non-thinning (3.493×10^3m/s) > medium (3.406×10^3m/s) > heavy (3.381×10^3m/s). It was also found that the Vtrees in the pruning treatments were in the following decreasing order: medium (3.485×10^3m/s) > heavy (3.424×10^3m/s) > non-thinning (3.372×10^3m/s). This indicates that the thinning had lower Vtrees than non-thinning, and the medium pruning had higher Vtrees than non-pruning.

The comparison of MOEtrees of Taiwania plantation trees treated with different thinning regimes is shown in Table 4. The variations of MOEtrees in the thinning treatments showed the following trend: non-thinning (82.908×10^3kgf/cm^2) > medium (78.731×10^3 kgf/cm^2) > heavy (77.431×10^3 kgf/cm^2). It was also found that the MOEtrees in the pruning treatments were in the following decreasing order: medium (86.223×10^3 kgf/cm^2) > non-thinning (78.3423×10^3 kgf/cm^2) > heavy (74.505×10^3 kgf/cm^2). This indicates that the thinning had lower MOEtrees than non-thinning, and the medium pruning had higher MOEtrees than heavy and non-pruning.

TABLE 3. *Comparison of ultrasonic wave speed (Vt) of Taiwania standing trees treated with different thinning and pruning regimes.*

			($\times10^3$m/s)
Treatment V	Heavy	Medium	Non
Thinning	3.381^a	3.406^a	3.493^b
Pruning	3.424^{ab}	3.485^b	3.372^a

TABLE 4. *Comparison of MOEt of Taiwania standing trees treated with different thinning and pruning regimes.*

			($\times10^3$kgf/cm^2)
Treatment DMOE	Heavy	Medium	Non
Thinning	77.431^a	78.731^a	82.908^b
Pruning	74.505^a	86.223^b	78.342^a

ULTRASONIC-WAVE PROPERTIES OF LUMBER

The ultrasonic-wave velocity (Vlumber) and dynamic modulus of elasticity (MOElumber) of the Taiwania specimen was measured by ultrasonic-wave technique. These results were analyzed using ANOVA, and the results are shown that the MOElumber and Vlumber were significantly influenced by the thinning (T) and pruning treatment (P). However, it is also clear that the effects of 9 rings after treatments (Y), thinning by pruning interaction (P×T), T × Y, P × Y, and T × P × Y on the MOElumber and Vlumber were not significant. Therefore, the effects of these treatment interactions were not analyzed any further.

The comparison of Vlumber of Taiwania plantation trees treated with different thinning regimes is shown in Table 5. The variations of Vs in the thinning treatments showed the following trend: non-thinning (4.715×10^3m/s) > heavy (4.513×10^3m/s) > medium (4.508×10^3m/s). It was also found that the Vlumber in the pruning treatments were in the following decreasing order: medium (4.630×10^3m/s) > heavy (4.593×10^3m/s) > non-thinning (4.513×10^3m/s). This indicates that the thinning had lower Vlumber than non-thinning, and the medium pruning had higher

TABLE 5. *Comparison of ultrasonic wave speed (Vs) of small, clear wood specimens obtained from different thinning and pruning regimes.*

			($\times 10^3$m/s)
Treatment V	Heavy	Medium	Non
Thinning	4.513^a	4.508^a	4.715^b
Pruning	4.593^{ab}	4.630^b	4.513^a

Vlumber than non-pruning. Bucur (1995) indicated that the increasing velocities values measured on pruned trees could be interpreted as the result of improved wood quality, and that the variability of pruned tree wood quality was smaller than that of the control trees. The principal effects of pruning on wood quality are the elimination of knots, the reduction of the influence of the juvenile wood, and the improvement of physical properties such as density and shrinkage (Bucur 1995; Zobel and van Buijtenen 1989).

The comparison of MOElumber of Taiwania plantation trees treated with different thinning regimes is shown Table 6. The variations of MOElumber in the thinning treatments showed the following trend: non-thinning (91.733×10^3kgf/cm^2) > medium (80.914×10^3 kgf/cm^2) > heavy (78.694×10^3 kgf/cm^2). It was also found that the MOElumber in the pruning treatments were in the following decreasing order: medium (89.814×10^3 kgf/cm^2) > non-pruning (81.388×10^3 kgf/cm^2) > heavy (80.140×10^3 kgf/cm^2). This indicates that the thinning group had lower MOElumber than non-thinning, and the medium pruning group had higher MOElumber than heavy and non-pruning groups.

In conclusion, the effects of thinning and pruning treatments on sample trees and specimens were evaluated, and the experiments were conducted using ultrasonic-wave method. It is shown that Taiwania trees and specimens with higher structural properties of occurred in the non-thinning and medium pruning treatments. These results are in agreement with those reported by previous authors (Lin et al. 2002) in which lumber with non-thinning and medium pruning treatments had greater wood density. Wang et al. (2001) indicated that lower density stands exhibited a trend toward decreased stress wave and static bending properties.

The average ultrasonic-wave velocity and dynamic modulus of elasticity value for specimens (Vlumber and MOElumber) were greater than that for standing trees (Vtrees and MOEtrees). However, some different results were observed in ultrasonic-wave properties. There could be several reasons for this. First, the stem of standing trees had green moisture content and growth stress. Second, the trunks of standing trees show more variation of surface conditions and more frequent occurrence of wood defects than do specimens (Wang et al. 2002). Third, other causes for the variation in results may include juvenile wood, cell type, and chemical components (percentage) that have various degrees of impact on ultrasonic properties of wood. The juvenile wood is characterized by shorter tracheid length, thinner cell walls in latewood, smaller degree of cellulose crystallinity, and larger microfibril angle in the tracheids (Wang and Chiu 1993).

TABLE 6. *Comparison of DMOE of small, clear wood specimens obtained from different thinning and pruning regimes.*

			($\times 10^3$kgf/cm^2)
Treatment DMOE	Heavy	Medium	Non
Thinning	78.694^a	80.914^a	91.733^b
Pruning	80.140^a	89.814^b	81.388^a

EFFECTS OF DBH ON ULTRASONIC-WAVE PROPERTIES

To understand the effect of growth conditions on the ultrasonic-wave properties, the relationships among the DBH, Vtrees, Vlumber, MOEtrees, and MOElumber are discussed. The Vtrees, Vlumber, MOEtrees, and MOElumber values decreased linearly with increasing DBH values. The following negative linear regressions were obtained.

Vtrees = – 0.0325DBH + 3.9809, $R^2 = 0.25$ F=8.28**,

MOEtrees = – 1.8285DBH + 111.35, R^2 = 0.36 F=13.85**,

Vlumber = – 0.0278DBH + 3.9073, R^2 = 0.17 F=5.0*, and

MOElumber = – 1.8976DBH + 113.41, R^2 = 0.25 F=8.17**

Legend:** and * denote that statistical results are very significant and significant, respectively.

Although the R^2 values were low, the models were significant at the $P<0.05$ confidence level for Vlumber and at the $P<0.01$ confidence level for Vtrees, MOEtrees, and MOElumber by the F test. This is similar to the result reported earlier by Wang and Chen (1992) and Chuang and Wang (2001). These studies indicated that in an even-age stand the sample trees with high DBH values usually had a lower density and modulus of elasticity, as well as lower ultrasonic-wave velocity.

CORRELATIONS BETWEEN ULTRASONIC-WAVE PROPERTIES

The values of Vtrees and MOEtrees of Taiwania increased with increases of the Vlumber and MOElumber, respectively. Their relationships could be represented by the following positive linear regression formulas:

Vtrees = 0.3392Vlumber + 1.8381, R^2 = 0.29 F=10.12**, and

MOEtrees = 0.5567MOElumber + 30.522, R^2 = 0.42 F=18.21**

Although their coefficients of determination (R^2) were lower, the regression models are highly significant (0.01 confidence level,**). This may be attributed to the variation in the properties of standing trees as a result of the green moisture content, growth stress and wood defects.

The variations of Vtrees, Vlumber, MOEtrees, and MOElumber in the thinning and pruning treatments showed a similar trend. This indicates that the thinning had lower Vtrees, Vlumber, MOEtrees, and MOElumber than non-thinning, and the medium pruning had higher Vtrees, Vlumber, MOEtrees, and MOElumber than non-pruning. The Taiwania trees and specimens in the non-thinning and medium pruning treatments had higher structural properties. This suggests that the ultrasonic-wave NDE technique used in this study provided relatively accurate and reliable ultrasonic-wave qualities of standing trees.

CONCLUSIONS

1. The heavy thinning treatment caused higher green moisture content than the medium and non-thinning treatments. However, the pruning treatments caused lower green moisture content than the non-pruning treatment.
2. The thinning had lower Vtrees, Vlumber, MOEtrees, and MOElumber than non-thinning, and the medium pruning had higher Vtrees, Vlumber, MOEtrees, and MOElumber than non-pruning. The higher structural properties of Taiwania trees and specimens occurred in the non-thinning and medium pruning treatments.
3. The Vtrees, Vlumber, MOEtrees, and MOElumber values decreased linearly with increasing DBH values in the same trees.
4. The values of Vtrees and MOEtrees of Taiwania increased with increases of the Vlumber and MOElumber, respectively.

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