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# Application of the drilling resistance method for annual ring characteristics: evaluation of Taiwania (*Taiwania cryptomerioides*) trees grown with different thinning and pruning treatments

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**Abstract** The effects of various thinning and pruning methods on the density profile and annual ring characteristics of Taiwania (*Taiwania cryptomerioides* Hay.) using the drilling resistance technique were investigated. The results showed that thinning caused wider annual rings than medium thinning or no thinning, and pruning caused narrower annual rings than no pruning. Moreover, the thinning treatment affected annual rings more effectively than the pruning treatment. The average ring density after the thinning treatments showed a trend as follows: no thinning > medium > heavy. This indicates that thinning reduces the average ring density. The average ring density after the pruning treatments showed a trend as follows: medium > no pruning > heavy. However, the differences between thinning and no thinning were not statistically significant. The percentage of latewood in Taiwania after these three thinning and pruning treatments are shown. The results with silvicultural treatments have the order: medium > not treated > heavy, but there are no statistically significant differences among thinning, pruning, and thinning where pruning interactions were observed. Moreover, there were highly significant negative relations between the average ring width and the various ring densities for Taiwania, but the determination coefficients were small. In addition, there was a highly positively significant relation between the latewood percentage and latewood width.

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**Key words** Drilling resistance · Annual ring characteristics · Taiwania · Thinning · Pruning · RESISTOGRAPH · Density profile

## Introduction

Taiwania (*Taiwania cryptomerioides*) is a monospecies of the *Taiwania* genus in Taiwan. Because of its rapid growth rate and good wood quality, Taiwania has become an important species for plantantions over the past few years. The management target of Taiwania plantations is to offer a continuous supply of large-diameter logs of high-quality wood.

It is recognized that the properties of wood are affected by the genetic factors of trees, environmental conditions of the site, and silvicultural practices, among other factors. 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 increase volume growth, and pruning treatment helps improve lumber quality.[1]

Both timber production and biodiversity conservation are important for forest management. Plantation trees will play an important role in supplying wood resources in the future. It should be known that volume growth and the lumber quality of plantation trees are important for the wood products industry. Accurate seedling propagation and suitable design of a plantation system not only may increase the biomass production of trees but may also achieve the goal of quality improvement in the trees.

The RESISTIGRAPH device has been shown to be a suitable tool for estimating the growth trends in trees. Drilling resistance is often used to detect tree annual rings in standing trees and decay in poles or timber structures. The RESISTOGRAPH measures the drilling resistance of a fine needle as it penetrates the wood. The mean levels of the RESISTOGRAPH charts closely correlate with the density of dry wood [coefficient of determination ($R^2$) > 0.8]. The density parameters the RESISTOGRAPH charts reveal (e.g., the earlywood and latewood areas in coniferous wood) correspond to those found in X-ray density charts. Moreover, the typical annual ring variations in the RESISTIGRAPH chart are similar to those in the X-ray chart.[2–10] The drilling resistance technique was found to be a good measure of the density profile of Taiwania.[11]

The purpose of this study was to investigate the effects of thinning and pruning treatments on the density profile and annual ring characteristics of Taiwania by the drilling resistance method. The results can provide basic information for future management practices and wood utilization of Taiwania.

## Material and methods

### Conditions of experimental forest site

The study site is located at an elevation of 1600 m in compartment 12, Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaohsiung Country, Taiwan, ROC. The mean annual temperature, relative humidity, and precipitation from 1986 to 1993 were 18.6°C, 81%, and 2280 mm, respectively. About 88% of the rainfall was concentrated during the period from April to September. Thus, the weather can be divided into a dry season and a rainy season.

### Experimental design

The area of the study site was about 2.0 ha. It was divided into 27 smaller plots, each being 0.04 ha in area including the buffer zone. The three types of thinning treatments were heavy thinning (basal area 28 $m^2$/ha at diameter at breast height, or DBH), medium thinning (33 $m^2$/ha), and no 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. The three pruning treatments were heavy pruning (4.5 m), medium pruning (3.6 m), and no pruning. The heavy and medium pruning treatments represented trees pruned 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 rate of 1750 trees/ha in 1980. Thinning and pruning treatments were implemented in 1990.

The 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. In total, 27 sample plots were designed. An outline of the thinning treatments of Taiwania stands are shown in Table 1.

### Experimental method

First, the diameter and height of each tree on the 27 small plots were measured. The average DBHs and tree heights are shown in Table 1. A mean diameter from the trees was selected from each plot, and a total of 27 sample trees were cut. One cross-sectional disk (10 cm thick) was cut from each sample tree at the position of its DBH. A diametrical strip (passed through the pith) was sawn from each disk in the same direction. The specimens were conditioned in a controlled-environment room: 20°C and 65% relative humidity. The RESISTIGRAPH measurements were done on air-seasoned wood (ca. 12%–15% moisture).

### Drill resistance method

The drilling resistance technique was used to measure the density profiles of these Taiwania wood samples. The RESISTOGRAPH drives a slender bit into the wood and measures the drilling resistance as it rotates. The needle bit has a shaft diameter of 1.5 mm and a maximum length of 400 mm. The tip of the needle was given special geometry and grinding. The drilling resistance concentrates at the tip because its width is double the diameter of the shaft (3 mm). The needle rotates continuously (ca. 1000 rpm). For wood, the feeding rate varies from 70 to 1000 mm/min. The drilling depth of the Rinn Tech RESISTOGRAPH 1410 version is 400 mm. Two 24-volt direct-current motors separately control the linear advancement and rotational speed of the drill.[8]

Using the linear relation between the drilling resistance value and the density as reported by Winistorfer et al.,[10] the following relations were established. The coefficients relat-

**Table 1.** Structure of thinning treatments of Taiwania stands

| Treatment | 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

ing to the point density were estimated by the following three equations.

$$D = \sum_{i=1}^{n} Di/n = c \times \sum_{i=1}^{n} Ri/n \quad (1)$$

$$c = n \times D \Big/ \sum_{i=1}^{n} Ri \quad (2)$$

$$D = c \times Ri \quad (i = 1 \text{ to } n) \quad (3)$$

where $n$ is the number of data points recorded for one density profile measurement; $D$ is the average board density; $c$ is the coefficient relating the resistance value and the density value; and $R$ is the drilling resistance value.

The power consumption of the drilling device is electronically measured relative to the drilling resistance. The drilling resistance values (profiles) were shown by the DECOM Win 1.5 computer program. The ring characteristics analysis was based on the hypothesis that there is a positive relation between the density boundary and the average maximum and minimum densities of the respective tree ring. The drilling resistance technique was then used to measure the density profiles of taiwania samples. The density boundary could be calculated by converting the drilling resistance values (from the RESISTOGRAPH chart) via a linear equation. The density boundary of Taiwania was obtained and used in a previous report.[11]

Based on the density boundaries, the various tree ring characteristics should be established for estimating some physical properties of the wood. The tree-ring contours are marked in the chart, and tree ring and control parameters (annual ring characteristics) are included, including the average tree ring widths (RW), earlywood widths (EWW), latewood widths (LWW), tree ring density (RD), earlywood density (EWD), latewood density (LWD), highest density (HD), lowest density (LD), and latewood percentage (LWP) in a ring. The drilling profile for the taiwania sample, revealing density variations inside tree rings caused by the density boundary between earlywood and latewood, are shown in Fig. 1.

### Analysis

An analysis of variance (multifactor ANOVA by the STATGRAPH software) was used to determine if the thinning and pruning levels significantly affected ring growth, average ring density, earlywood and latewood density, and the percent of latewood. $F$ values were computed to test for the significance of treatments. When the treatment effects were significant, means were compared using Duncan's multiple range test.

## Results and discussion

### DBHs and heights of trees

The ANOVA of the DBH and tree height of Taiwania plantation trees subjected to various thinning and pruning treatments are shown in Table 2. The effects of thinning on the DBH were statistically significant. Pruning and thinning through the pruning interaction effect on DBH and tree height were not significant. Thinning and pruning did not have any effect on tree height.

The DBHs and heights of the mean diameter of the trees from three thinning and pruning plots are shown in Table 3. As far as the thinning is concerned, the largest DBH of the mean diameter of the trees was observed with heavy thinning (28.03 cm), followed in order by medium thinning (26.56 cm) and no thinning (23.53 cm). Medium thinning produced the tallest trees (15.8 m), followed in order by no thinning (15.5 m) and heavy thinning (15.21 m). With pruning, the largest DBH of the mean diameter of the trees was observed with no pruning (26.17 cm) followed by medium

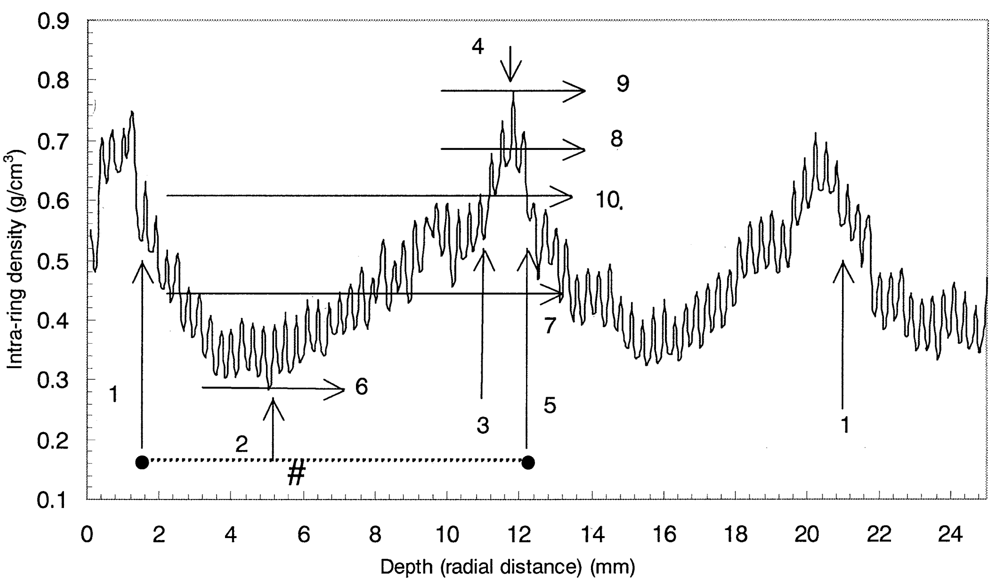


**Fig. 1.** Drilling profile for Taiwania plantation wood revealing density variations inside tree rings caused by the density boundary between earlywood and latewood zones. $x$-Axis: #, a growth ring; *1, 3, 5*, density boundary of earlywood and latewood; *2*, minimum density in a ring; *4*, maximum density in a ring. $y$-Axis: *6*, minimum density in a ring; *7*, average earlywood density in a ring; *8*, average latewood density in a ring; *9*, maximum density in a ring; *10*, density boundary of earlywood and latewood

**Table 2.** ANOVA of DBH and tree height of Taiwania plantation trees subjected to various thinning and pruning treatments

| Variance | Thinning intensity | Pruning intensity | Thinning × pruning interaction | Residual | Total |
|---|---|---|---|---|---|
| Degrees of freedom | 2 | 2 | 4 | 18 | 26 |
| DBH | | | | | |
| Sum of squares | 94.70 | 0.27 | 7.86 | 53.45 | 156.29 |
| Mean square | 47.35 | 0.13 | 1.96 | 2.97 | |
| *F* value | 15.95[a] | 0.05 | 0.66 | | |
| Tree height | | | | | |
| Sum of squares | 1.56 | 1.58 | 2.55 | 22.36 | 28.05 |
| Mean square | 0.78 | 0.79 | 0.64 | 1.24 | |
| *F* value | 0.63 | 0.64 | 0.51 | | |

ANOVA, analysis of variance
[a]Statistical differences between treatments were highly significant ($P \leq 0.01$)

**Table 3.** Comparison of DBH and tree height of Taiwania plantation trees treated with various thinning and pruning regimens

| Parameter | Results, by degree of treatment | | |
|---|---|---|---|
| | Heavy | Medium | None |
| DBH (cm) | | | |
| Thinning | 28.03[a] | 26.56[a] | 23.53[b] |
| Pruning | 25.92[a] | 26.03[a] | 26.17[a] |
| Tree height (m) | | | |
| Thinning | 15.21[a] | 15.80[a] | 15.50[a] |
| Pruning | 15.54[a] | 15.19[a] | 15.78[a] |

Results are means. Means within a given row with the same letter (a or b) are not significantly ($P \leq 0.05$) different, as determined by Duncan's multiple range test

pruning (26.03 cm) and heavy pruning (25.92 cm). No pruning produced the tallest trees (15.78 m), followed by heavy pruning (15.54 m) and medium pruning (15.21 m). Obviously, heavy thinning affected DBH growth most effectively followed by medium and no thinning because heavy thinning produced larger growth spaces than those of medium and no thinning.

The results showed that the DBHs of individual trees were significantly increased by thinning but decreased by pruning. This implies that the pruning treatment may suppress DBH growth. These results are similar to those reported earlier by Wang and Chen.[12] Wang and Chen[12] also indicated that the mechanism of the greater effect of the growth space on DBH than that of the height growth of the tree is not yet fully understood. Koga et al.[13] noted that heavy thinning significantly affected the growth rate at the position of the DBH, but it had little effect on wood density.

## Width of growth rings

The drilling profile of the Taiwania sample was measured by a drill device (RESISTOGRAPH), and the density profiles were then calculated from the drilling resistance values. A record of the drilling resistance and the density profiles of the Taiwania sample determined by the drilling resistance technique is shown in Fig. 2.

The annual-ring, earlywood, and latewood widths of Taiwania trees were subjected to various thinning and pruning methods performed with the RESISTOGRAPH technique. These figures were analyzed using ANOVA, and the results are shown in Table 4. The annual-ring and earlywood widths were significantly influenced by the thinning and pruning treatments, whereas the latewood width was not statistically affected. It was also obvious that the effects of thinning by pruning interaction on the annual-ring, earlywood, and latewood widths were not significant. Therefore, the effects of thinning with a pruning interaction were not analyzed any further.

A comparison of the average annual-ring, earlywood, and latewood widths of Taiwania plantation trees treated with various thinning regimens are shown in Table 5. The variations in the annual-ring width after the thinning treatments showed the following trend: heavy (5.81 mm) > medium (5.15 mm) > no (4.66 mm) thinning. It was also found that the width of earlywood after the thinning treatments were in the following decreasing order: heavy (5.10 mm) > medium (4.47 mm) > no (4.00 mm) thinning. The width of the latewood after the thinning treatments showed a trend as follows: heavy (0.72 mm) > medium (0.69 mm) > no (0.67 mm) thinning. Significant differences (0.05 level) existed for annual-ring and earlywood widths among the three thinning treatments. However, no significant differences were shown for the latewood width among the three thinning treatments. This indicates that heavy thinning produced wider annual rings than medium or no thinning.

The change in annual-ring, earlywood, and latewood widths years after thinning are shown in Figs. 3–5. It was found that the values for the annual-ring and earlywood widths slightly decreased with the increase in years following thinning treatment. However, the latewood widths showed a constant tendency during this thinning period. It was also obvious that the annual-ring and earlywood widths were more significantly affected by heavy thinning than by medium or no thinning for 2–7 years after thinning but not for the other years. In general, a wide growth ring is always the result of a widely spaced plantation. In this study, the thinned plots had a wider plantation than medium and not thinned plots.

These results were similar to the results reported by Wang and Chen[12] and Koga et al.[13] The former indicated that the Japanese cedar trees grown at relatively wide spac-

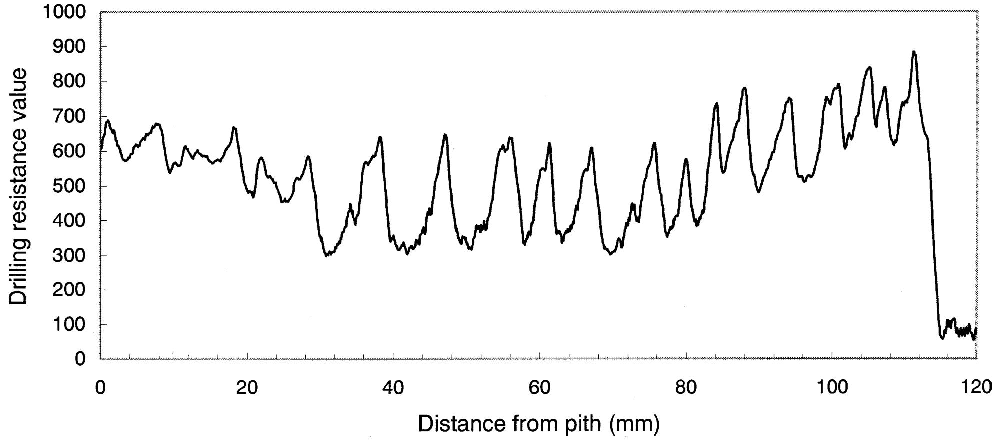


**Fig. 2.** Drilling resistance record measured in Taiwania samples from tree 14

**Table 4.** ANOVA of ring characteristics of Taiwania plantation trees subjected to different thinning and pruning treatments

| Variance | Thinning intensity | Pruning intensity | Thinning × Pruning interaction | Residual | Total |
|---|---|---|---|---|---|
| Degrees of freedom | 2 | 2 | 4 | 45 | 53 |
| Width | | | | | |
| Ring | | | | | |
| Sum of squares | 11.91 | 6.64 | 8.07 | 39.67 | 66.28 |
| Mean square | 5.95 | 3.32 | 2.02 | 0.88 | |
| *F* value | 6.75** | 3.77* | 2.29 | | |
| Earlywood | | | | | |
| Sum of squares | 10.85 | 5.56 | 6.33 | 32.99 | 55.73 |
| Mean square | 5.42 | 2.78 | 1.58 | 0.73 | |
| *F* value | 7.40** | 3.80* | 2.16 | | |
| Latewood | | | | | |
| Sum of squares | 0.02 | 0.07 | 0.55 | 2.86 | 3.50 |
| Mean square | 0.01 | 0.03 | 0.14 | 0.06 | |
| *F* value | 0.16 | 0.52 | 2.17 | | |
| Density | | | | | |
| Ring | | | | | |
| Sum of squares | 0.006 | 0.006 | 0.006 | 0.031 | 0.049 |
| Mean square | 0.003 | 0.003 | 0.001 | 0.0001 | |
| *F* value | 4.11* | 4.66* | 2.02 | | |
| Earlywood | | | | | |
| Sum of squares | 0.004 | 0.013 | 0.007 | 0.103 | 0.127 |
| Mean square | 0.002 | 0.007 | 0.002 | 0.002 | |
| *F* value | 0.81 | 2.85 | 0.82 | | |
| Latewood | | | | | |
| Sum of squares | 0.004 | 0.004 | 0.006 | 0.051 | 0.066 |
| Mean square | 0.002 | 0.002 | 0.001 | 0.001 | |
| *F* value | 1.98 | 1.95 | 1.25 | | |
| Highest | | | | | |
| Sum of squares | 0.011 | 0.007 | 0.004 | 0.081 | |
| Mean square | 0.005 | 0.004 | 0.001 | 0.002 | 0.102 |
| *F* value | 2.93 | 2.00 | 0.50 | | |
| Lowest | | | | | |
| Sum of squares | 0.009 | 0.004 | 0.005 | 0.027 | 0.045 |
| Mean square | 0.004 | 0.002 | 0.001 | 0.0001 | |
| *F* value | 7.22 | 3.31 | 2.31 | | |
| Latewood percentage | | | | | |
| Sum of squares | 45.02 | 7.39 | 189.87 | 982.97 | 1225.3 |
| Mean square | 22.51 | 3.69 | 47.47 | 21.84 | |
| *F* value | 1.03 | 0.17 | 2.17 | | |

*Statistical differences between treatments are significant ($P \leq 0.05$)
**Statistical differences between treatments are highly significant ($P \leq 0.01$)

ing had wider annual ring widths. The latter authors, studying the effects of thinning on Japanese larch, indicated that trees from thinned plots showed a significant increase in annual-ring, earlywood, and latewood widths after thinning.

A comparison of annual-ring, earlywood, and latewood widths of Taiwania plantation trees treated with various pruning regimens are shown in Table 6. The variations of annual-ring widths after the pruning treatments showed the

**Table 5.** Comparison of ring characteristics of Taiwania plantation trees treated with various thinning regimens

| Characteristic | Results, by treatment | | |
|---|---|---|---|
| | Retaining 27.5 $m^2$/ha (heavy) | Retaining 32.5 $m^2$/ha (medium) | No thinning |
| Width (mm) | | | |
| Ring | 5.81[a] | 5.15[b] | 4.66[b] |
| Earlywood | 5.10[a] | 4.47[b] | 4.00[b] |
| Latewood | 0.72[a] | 0.69[a] | 0.67[a] |
| Density (g/$cm^3$) | | | |
| Ring | 0.38[a] | 0.39[ab] | 0.40[b] |
| Earlywood | 0.37[a] | 0.37[a] | 0.39[a] |
| Latewood | 0.50[a] | 0.51[a] | 0.52[a] |
| Highest | 0.53[a] | 0.55[a] | 0.57[a] |
| Lowest | 0.30[a] | 0.28[a] | 0.27[a] |
| Latewood percentage | 12.59[a] | 14.54[a] | 14.52[a] |

Results were averaged over a posttreatment period of 9 years. The means within a given row with the same letter (a or b) are not significantly ($P \le 0.05$) different, as determined by Duncan's multiple range test

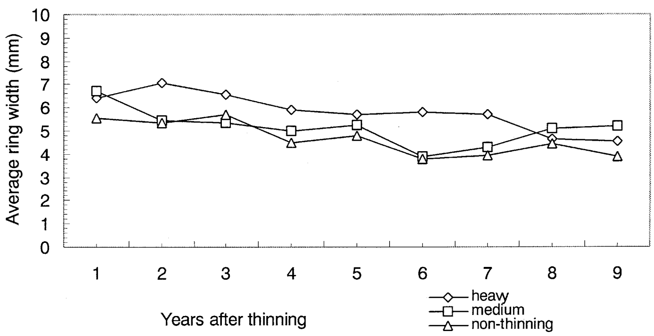


**Fig. 3.** Average ring width with various thinning treatments

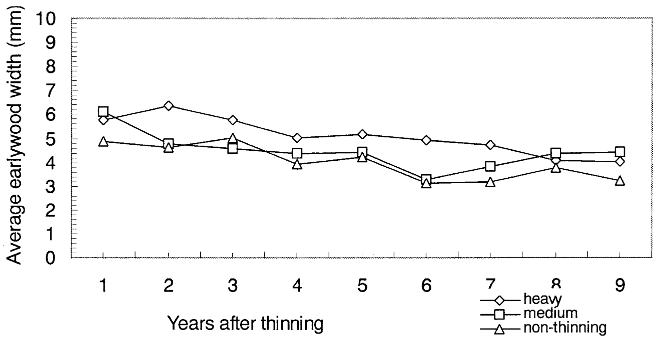


**Fig. 4.** Average earlywood width with various thinning treatments

following trend: no pruning (5.58 mm) > heavy pruning (5.31 mm) > medium pruning (4.73 mm). It was also found that the earlywood widths after the pruning treatments were in decreasing order as follows: no pruning (4.83 mm) > heavy pruning (4.66 mm) > medium pruning (4.08 mm). The latewood widths after the pruning treatments showed a trend as follows: no pruning (0.72 mm) > heavy pruning (0.67 mm) > medium pruning (0.66 mm). The significant differences (0.05 level) in annual-ring and earlywood widths among these three pruning treatments were observed. However, there was no significant difference in latewood

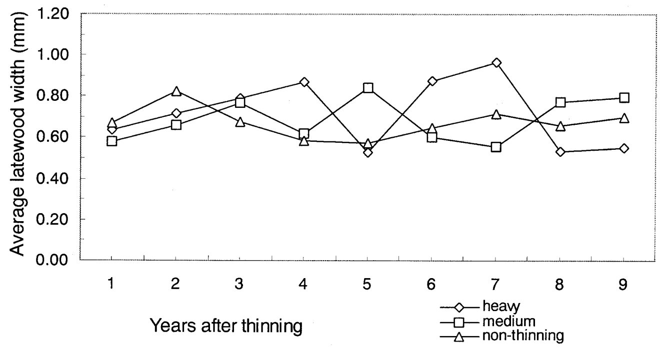


**Fig. 5.** Average latewood width with various thinning treatments

width among these pruning treatments. Based on this result, it can be seen that pruning treatment causes narrower annual rings than does the no thinning treatment. This result was similar to that in the report of Zobel and van Buijtenen,[1] who indicated that the earlywood proportion in an annual ring of radiata pine is reduced by pruning treatment.

The variations in annual-ring, earlywood, and latewood widths were followed by growth during these pruning treatment periods. A similar trend was found for thinning treatment.

## Wood density in an annual ring

The average wood densities in an annual ring in an air-dried specimen cut from the trees subjected to various thinning and pruning treatments were analyzed using a multifactor ANOVA test. The results are shown in Table 4. Significant differences in the average ring densities were observed after the thinning and pruning treatment. However, there were no significant differences among average ring density values for the thinning by pruning interaction treatments. Therefore, the effects of thinning by pruning interaction on the average values of wood density were not analyzed further.

**Table 6.** Comparison of ring characteristics of Taiwania plantation trees treated with various pruning regimens

| Characteristics | Results, by treatment | | |
|---|---|---|---|
| | Heavy pruning (at 4.5 m height) (heavy) | Medium pruning (at 3.6 m height) (medium) | No pruning |
| Width (mm) | | | |
| Ring | 5.31[ab] | 4.73[a] | 5.58[b] |
| Earlywood | 4.66[a] | 4.08[b] | 4.83[a] |
| Latewood | 0.67[a] | 0.66[a] | 0.72[a] |
| Density (g/cm$^3$) | | | |
| Ring | 0.38[a] | 0.40[b] | 0.39[ab] |
| Earlywood | 0.36[a] | 0.40[a] | 0.38[a] |
| Latewood | 0.50[a] | 0.52[a] | 0.50[a] |
| Highest | 0.54[a] | 0.57[a] | 0.54[a] |
| Lowest | 0.27[a] | 0.29[a] | 0.29[a] |
| Latewood percentage (%) | 13.49[a] | 14.38[a] | 13.79[a] |

Results were averaged over a posttreatment period of 9 years. The means within a given row with the same letter (a or b) are not significantly ($P \leq 0.05$) different, as determined by Duncan's multiple range test

The differences in air-dried wood density in annual rings, earlywood, and latewood for the various thinning treatments were analyzed using Duncan's multiple new-range test. The results are shown in Table 5. It was found that the average values of the air-dried density in the annual ring obtained from nonthinned trees were significantly higher than those for the heavily thinned trees. The variations of ring density showed a trend as follows: no thinning (0.40 g/cm$^3$) > medium thinning (0.39 g/cm$^3$) > heavy thinning (0.38 g/cm$^3$). However, there were no significant differences among earlywood and latewood densities for the various thinning treatments. This study indicated that thinning may not affect earlywood density but may cause a slightly decrease in latewood density. Similar results have been reported for the earlywood and latewood density of Douglas fir.[14] The no-thinning treatment not only produced higher annual-ring, earlywood, and latewood densities but also greater variation. This was contrary to the trend for the differences in annual-ring width among the various thinning treatments. Based on this result, it can be seen that heavy thinning reduces the average values for the air-dried density in the annual ring. This result was similar to that reported by Koga et al.[13].

A comparison of the average ring density of Taiwania plantation trees treated with various pruning regimens is shown in Table 6. The variations in average ring density in the pruning treatments showed the following trend: medium pruning (0.40 g/cm$^3$) > no pruning (0.39 g/cm$^3$) > heavy pruning (0.38 g/cm$^3$). Based on an analysis of Duncan's new-range test, a significant difference between woods that underwent heavy and medium pruning was observed. However, no significant differences existed between pruning and no pruning.

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

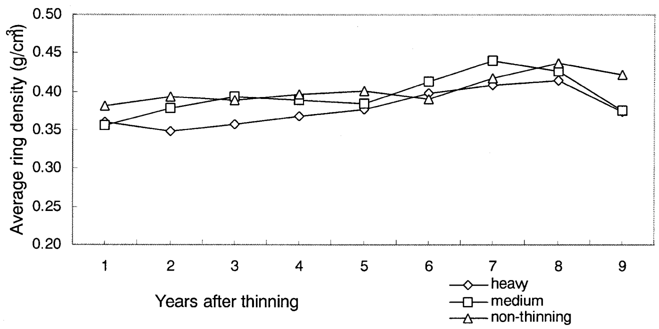


**Fig. 6.** Average ring density with various thinning treatments

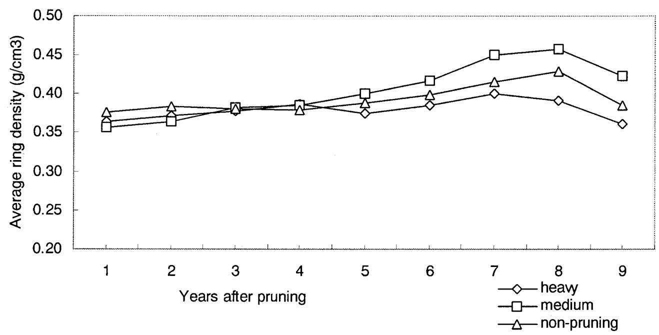


**Fig. 7.** Average ring density with various pruning treatments

The variations in ring density with time after thinning for the three thinning treatments are shown in Fig. 6. It was found that the variations in ring density with time after thinning increased slightly except at the eighth and ninth years. There was no variation in ring density after various thinning treatments during the 9 years after thinning. The variations in ring density with the time after pruning for the three pruning treatments are shown in Fig. 7. It was found that the variations in the ring density with time after pruning increased slightly, except during the ninth year. There was no variation in ring density for various pruning methods at 1–4 years, whereas there was variation at 5–9 years after pruning. The trend was as follows: medium pruning > no pruning > heavy pruning.

The average values for earlywood density, latewood density, highest density, and lowest density of air-dried specimens from the trees cut after the three thinning and pruning methods were analyzed using a multifactor ANOVA test and are shown in Table 4. No significant differences among thinning, pruning, and thinning by pruning interaction were observed. A comparison of average earlywood density, latewood density, highest density, and lowest density of Taiwania plantation trees with various thinning regimens is shown in Table 5. Based on these results after the thinning treatments, the highest values of earlywood density, latewood density, and highest density appeared in wood that was not thinned, followed by medium thinning; the lowest values were associated with heavy thinning. However, the lowest density had the order: heavy > medium > no thinning.

A comparison of average earlywood density, latewood density, highest density, and lowest density of Taiwania plantation trees with various pruning regimens is shown in Table 6. A decreasing order was observed as follows: medium pruning > no pruning > heavy pruning.

### Percent of latewood

The average latewood percentages of air-dried specimens from the three thinning and pruning methods were analyzed using a multifactor ANOVA test (Table 4). No significant differences among thinning, pruning, or thinning by pruning interaction were observed.

The differences in latewood percentage among the thinning methods during this experiment period were analyzed using Duncan's multiple new-range test. The results are summarized in Table 5. A decreasing order was found as follows: medium thinning ≒ non-thinning > heavy thinning, but, the differences were not significant. This meant that the latewood percentage of Taiwania was not affected by thinning. This result was similar to that reported by Koga et al.,[13] who indicated that thinning had no effect on the percentage of latewood in Japanese larch. Some studies have also reported that thinning had no or only minor effects on the latewood percentage.[15–19]

### Regression equations of ring characteristics

The linear regression equations of various ring characteristics for Taiwania are shown in Table 7. In this study there were highly significant negative relations between the average ring width (RW) and various ring densities (RD, EWD, LWD, LD) for Taiwania. However, the determination coefficients were low for the above-mentioned factors.

There were positive significant relations between the average RD and various ring densities (EWD, LWD, HD, LD) for Taiwania, but the determination coefficients were low between RD and EWD. The order of determination coefficients was RD and LD, RD and LWD, and RD and HD.

**Table 7.** Linear regression equations for various ring characteristics of Taiwania

$Y = a \times +b$ (linear regression equations)

| *X* | *Y* | a | b | $R^2$ | *F* | Significance |
|---|---|---|---|---|---|---|
| RW | RD | −0.01 | 0.43 | 0.10 | 51.4 | ** |
| RW | EWD | −0.01 | 0.4 | 0.03 | 14.7 | ** |
| RW | LWD | −0.01 | 0.5 | 0.03 | 13.6 | ** |
| RW | HD | −0.03 | 0.56 | 0.01 | 1.8 | ** |
| RW | LD | −0.01 | 0.34 | 0.19 | 110.4 | ** |
| RD | EWD | 0.39 | 0.22 | 0.12 | 64.6 | ** |
| RD | LWD | 0.88 | 0.16 | 0.50 | 479 | ** |
| RD | HD | 1.05 | 0.14 | 0.42 | 344 | ** |
| RD | LD | 0.80 | −0.03 | 0.64 | 845 | ** |
| RW | LWP | −0.65 | 17.3 | 0.03 | 11.4 | ** |
| EWW | LWP | −1.65 | 21.4 | 0.13 | 72.1 | ** |
| LWW | LWP | 14.8 | 3.6 | 0.65 | 903 | ** |
| RD | LWP | 54.9 | −7.6 | 0.11 | 59.6 | ** |

RW, ring width; EWW, earlywood wide; LWW, latewood wide; RD, ring density; EWD, earlywood density; LWD, latewood density; HD, highest density; LD, lowest density; LWP, latewood percentage; $R^2$, coefficient of determination

**Significant at 1% level, by the *F* test

In addition, the relation between the percentage of latewood (LWP) and ring width (RW, EWW, LWW, RD) was examined by regression analysis for Taiwania. The following negative linear regression formulas were obtained between LWP and RW, and LWP and EWW, for the three silvicultural treatments. This is similar to the result reported earlier by Wang and Chen.[12] The following linear position regression formulas were obtained between LWP and EWW, and LWP and RD. However, the determination coefficients were also low between RW and LWP, EWW and LWP, and RD and LWP. There were extremely positive significant relations between LWP and LWW for Taiwania.

## Conclusions

Based on the results obtained in this study, the following conclusions may be drawn: (1) Significant differences (0.05 level) existed among the annual-ring and earlywood widths after various thinning treatments, but there was no variation in the latewood width after thinning. (2) The highest wood ring densities appeared in wood cut from trees with no thinning followed by medium thinning; the lowest densities were seen after heavy thinning. (3) The variations in average ring density after the pruning treatments showed a trend as follows: medium pruning > no pruning > heavy pruning. There was a significant difference between woods after heavy and medium pruning. No significant differences existed between pruning and no pruning. (4) The percentages of latewood in Taiwania after these three thinning and pruning methods with silvicultural treatments are in the order: medium > not treated > heavy. (5) There were highly significant negative relations between the average ring width (RW) and various ring densities (RD, EWD, LWD, LD) for Taiwania. A positive significant relation between the LWP and LWW for Taiwania was observed.

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