J Wood Sci (2003) 49:444–449
DOI 10.1007/s10086-002-0495-5

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Effects of thinning and pruning on knots and lumber recovery of Taiwania (*Taiwania cryptomerioides*) planted in the Lu-Kuei area

Received: May 21, 2002 / Accepted: October 11, 2002

Abstract This study investigated the effects of various thinning and pruning methods on the knots (number and size) and lumber recovery from Taiwania (*Taiwania cryptomerioides* Hay.) plantation trees. The results showed that heavy thinning caused more knots and larger-diameter knots than medium or no thinning; moreover, pruning caused fewer numbers of knots and smaller-diameter knots than no pruning. Better-quality Taiwania trees occurred with the no-thinning/no-pruning treatments, as shown by analyzing the knots, although the results also showed that the healing process seemed to have produced not completely clear wood during the 9 years after the pruning treatment. The thinning intensity slightly enhanced the lumber recovery of logs. Pruning did not affect lumber recovery from taiwania trees and logs. Thinning increased the lumber recovery per tree due to an increase in the diameter at breast height.

Key words Taiwania (*Taiwania cryptomerioides* Hay.) · Thinning · Pruning · Knots · Lumber recovery

Introduction

Thinning and pruning forest stands have been recognized as important silvicultural tools for manipulating the growth of plantation trees. Thinning helps increase volume growth, and pruning helps improve lumber quality.[1] This is of concern, as the forest industry has become increasingly concerned about the impact of growth on the wood quality and lumber recovery from forest plantations.

Wood quality is significantly affected by knot characteristics in plantation trees.[2,3] Detection of knots in Taiwania logs or lumber is especially important because knots are the most numerous and most severe defects. Reductions in lumber grade, strength, processing, and yield associated with the number and size of knots is often qualitatively attributed to grain deviation in the wood immediately surrounding the knots. Confirming this, several reports have demonstrated a relation among number and size of knots, lumber grade, and wood quality.[2,4–11] Fisher[9] and Chiu et al.[10,11] have reported the effects of thinning or pruning on the branch size and wood quality in plantations. Moreover, in many situations the frequency of the knots is used as an important indicator of wood quality for visual grading.

Lumber recovery is one of the most common output indicators used to evaluate the efficiency of a mill. The product yield is an important factor when determining the profitability of the lumber industry. Some studies have investigated the effects of certain factors (e.g., log diameter, taper, quality, lumber size, sawing method) on lumber recovery (lumber yield, grade recovery, timber yield, conversion ratio) from logs and trees.[12–15] Also, a few researchers have reported the effects of thinning and pruning on lumber recovery of plantation trees.[16–18]

This present study investigated the effects of thinning and pruning on the number and size of knots on the surface of logs and on the lumber recovery of Taiwania trees. The results can provide basic information for estimating and examining wood utilization of plantation trees in lumber manufacturing.

Material and methods

Conditions of experimental forest site

The study site was located at an elevation of 1600 m in compartment 12, Liukuei Experimental Forest of the

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Table 1. Outline of various 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)						
First sample	11	1801	16.89	9.81	41.95	195.47
Second sample	20	1528	23.53	15.50	66.44	463.45

DBH, diameter at breast height

Taiwan Forestry Research Institute (TFRI), Kaohsiung Country, Taiwan, ROC. The mean annual temperature, relative humidity, and precipitation during 1986–1993 were 18.6°C, 81%, and 2280 mm, respectively.

Experimental design

The area of the study site, about 2.0 ha, was divided into 27 smaller plots, each being 0.04 ha including the buffer zone. The three types of thinning were heavy thinning [basal area 28 m^2/ha at the diameter at breast height (DBH)], medium thinning (33 m^2/ha), and no thinning (42 m^2/ha). The harvested stocks after heavy and medium thinning from the original 42 (m^2/ha) measured 28 and 33 m^2/ha, respectively. The three types of pruning were heavy pruning (4.5 m), medium pruning (3.6 m), and no pruning. For the heavy and medium pruning treatments, trees were pruned from the root base upward to 4.5 or 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. Outlines of the various thinning treatments of Taiwania stands are shown in Table 1.

Three levels of thinning were combined with three levels of pruning, resulting in nine silvicultural conditions in this study. The same thinning and pruning treatments were repeated three times. In total, then, 27 sample plots were designed.

Experimental method

First, the diameter and height of each tree on the 27 small plots were measured. One mean diameter tree was selected from each plot, so a total of 27 sample trees were cut in 2000. Each sample tree was cut into logs at 2.2-m intervals from the base to the top. After the number and size of the knots were recorded based on the conditions of each log face, the logs were further band-sawed into lumber sequentially according to the cant sawing method. All were 2.2 m long with a nominal width and thickness of 10 × 4 cm and 10.0 × 1.4 cm. Recovery was calculated as the lumber volume divided by the log volume, with the lumber volumes calculated from the full size of each piece.[8]

Statistical analysis

An analysis of variance (ANOVA) was used to determine if the thinning and pruning levels significantly affected knots and lumber recovery. The *F* values were computed to test for the significance of the treatments. When the treatment effects were significant, means were compared using Duncan's multiple range test.

Results and discussion

Knots on log surface

The effects of thinning, pruning, and thinning plus pruning on the number of knots per 1-m log were not significant by ANOVA. A comparison of the number of knots treated with various thinning, pruning, and thinning plus pruning interaction regimens are shown in Table 2. The variations of number of knots according to the thinning treatments showed the following trend: heavy (11.64/m) > medium (9.57/m) > no (9.28/m) thinning. This indicates that heavy thinning produced more knots than medium or no thinning.

In this study, the thinned plots had a wider plantation than medium or not thinned plots, and in general more knots are the result of a widely spaced plantation. The principal effects of thinning, or a wider plantation, are the encouragement of branch growth and reduced influence of the natural pruning effect.

The DBH and height growth of individual trees was previously shown to be significantly increased by intermediate and heavy thinning.[18] Fisher[9] indicated that lower stockings produced larger branches. Kano et al.[19–20] and Chiu et al.[10] also indicated that there were more branches in superior trees than in inferior trees.

The variation in the number of knots based on pruning showed the following trend: no pruning (10.97/m) > medium pruning (9.87/m) > heavy pruning (9.84/m). Based on these results, it can be seen that pruning reduces the number of knots compared to that seen with no pruning. However, the difference in the number of knots among these pruning treatments was not significant. Chiu et al.[10] indi-

Table 2. Knots in Taiwania plantation trees treated with various thinning and pruning regimens

Treatment	No. of knots/1-m log
Thinning	
Heavy	11.64
Medium	9.57
None	9.28
Pruning	
Heavy	9.84
Medium	9.87
None	10.79
T × P	
BC	7.80
CA	8.24
CB	8.30
BB	10.17
AA	10.55
BA	10.73
AB	11.14
CC	11.31
AC	13.25

AA, heavy thinning and heavy pruning; AB, heavy thinning and medium pruning; AC, heavy thinning and no pruning; BA, medium thinning and heavy pruning; BB, medium thinning and medium pruning; BC, medium thinning and no pruning; CA, no thinning and heavy pruning; CB, no thinning and medium pruning; CC, no thinning and no pruning

cated that the average number of knots per unit of lumber surface had a negative relation with the distance from the pith, whereas the average knot size (diameter) had a positive relation. The pruning treatment decreased the number of knots per tree because the trunk promoted occlusion of the pruning wounds. The variations of number of knots produced by the thinning plus pruning interaction are shown in Table 2.

Live knots on log surface

There is a relation between the number of live knots and the elimination rate of live branches, artificial pruning profitability, and occlusion of pruning wound. This had a great effect on the future of the trees' growth and the occurrence of clear wood after pruning.

The numbers of live knots on the surface of logs were analyzed using ANOVA, which indicated that the effects of thinning, pruning, and thinning plus pruning on the number of live knots per 1-m log were not significant. A comparison of the number of live knots treated with various thinning, pruning, and thinning plus pruning interaction regimens are shown in Table 3.

The variations in the number of live knots per 1-m log according to the thinning treatments showed the following trend: heavy (8.03/m) > medium (6.58/m) > no (6.37/m) thinning. This indicates that heavy thinning produced more live knots than medium or no thinning. The variations in the number of knots after pruning showed the following trend: medium (7.55/m) > heavy (7.22/m) > no (6.22/m) pruning. Based on these results, it can be seen that pruning reduces the number of knots compared to no pruning. However, there was no significant difference in the number of knots among these thinning and pruning treatments. Variations in the number of knots after exposure to the thinning plus pruning interaction are shown in Table 3.

Table 3. Live knots in Taiwania plantation trees treated with various thinning and pruning regimens

Treatment	No. of knots/1-m log
Thinning	
Heavy	8.03
Medium	6.58
None	6.37
Pruning	
Heavy	7.22
Medium	7.55
None	6.22
T × P	
BC	4.97
CC	5.54
CB	6.53
BA	6.99
CA	7.05
AA	7.63
BB	7.77
AC	8.14
AB	8.33

Dead knots on log surface

There is a relation between the number of dead knots and the natural pruning function, artificial pruning efficiency, and healing process of the branch. The numbers of dead knots on the surface of logs were analyzed using ANOVA, which showed that the effects of pruning on the number of dead knots per 1-m log were significant. Moreover, the knots were not statistically significantly affected by thinning or by thinning plus pruning.

A comparison of the number of dead knots treated with various thinning, pruning, or thinning plus pruning regimens are shown in Table 4. The variations in the number of dead knots per 1-m log after the thinning showed the following trend: heavy (3.61/m) > medium (2.99/m) > no (2.91/m) thinning. This indicates that heavy thinning produced more dead knots than medium and no thinning. However, the differences in the numbers of dead knots among these thinning treatments were not significant.

Variations in the number of dead knots after pruning showed the following trend: no pruning (4.57/m) > heavy pruning (2.62/m) > medium pruning (2.32/m). This indicates that pruning reduces the number of dead knots compared to no pruning. In addition, there was a significant difference in the number of dead knots between the pruned and not pruned samples. This result is similar to those reported earlier by Chiu et al.,[10] who indicated that the number of dead knots was significantly influenced by pruning. The variations in the number of knots produced by the thinning plus pruning interaction are shown in Table 4.

Table 4. Dead knots in Taiwania plantation trees treated with various thinning and pruning regimens

Treatment	No. of knots/1-m log*
Thinning (T)	
Heavy	3.61a
Medium	2.99a
None	2.91a
Pruning (P)	
Heavy	2.62a
Medium	2.32a
None	4.57b
T × P	
CA	1.19
CB	1.77
BB	2.40
AB	2.80
BC	2.83
AA	2.92
BA	3.74
AC	5.10
CC	5.77

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

Table 5. Average diameters of knots for Taiwania plantation trees treated with various thinning and pruning regimens

Treatment	Average diameter of knots (cm)*
Thinning (T)	
Heavy	2.36a
Medium	2.25ab
None	2.12b
Pruning (P)	
Heavy	2.12a
Medium	2.13a
None	2.48b
T × P	
CA	1.92a
CB	2.02a
BB	2.16a
AA	2.17a
AB	2.22a
BA	2.27a
BC	2.34a
CC	2.42a
AC	2.69a

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

Size of knots on log surface

The sizes of the knots on the surface of logs were analyzed using ANOVA, which found that the effects of thinning and pruning on the average diameter of the knots were significant. However, the knot size was not statistically significantly affected by the thinning plus pruning interaction.

Table 5 shows the average diameters of knots treated with various thinning, pruning, and thinning plus pruning regimens. The variations in the average diameters of the knots after thinning showed the following trend: heavy (2.36 cm) > medium (2.25 cm) > no (2.12 cm) thinning. This indicates that heavy thinning produced larger-diameter knots than medium or no thinning. The variations in the diameters of the knots after pruning showed the following trend: no pruning (2.48 cm) > medium pruning (2.13 cm) > heavy pruning (2.12 cm). Based on these results it can be seen that pruning causes smaller-diameter knots than no pruning. Variations in the numbers of knots after the thinning plus pruning interaction are shown in Table 5.

Fisher[9] indicated that the lower stockings produced larger branches; moreover, spacing was positively correlated with the area of live knots and inversely correlated with the area of dead knots. Chiu et al.[10] indicated that the average diameter of knots was larger with superior tree growth than with inferior tree growth and that pruning was important to promote the grade of Taiwania lumber.

In conclusion, we evaluated the effects of thinning and pruning on lumber quality by analyzing knots from sample trees. The results showed that better-quality Taiwania trees were produced after no thinning and heavy pruning. However, other results indicated that the numbers and sizes of the knots were not statistically affected by pruning or not pruning. This may be because artificial or natural pruning produces clear wood by encouraging occlusion of pruning wounds, although the healing process seemed not to produce completely clear wood even 9 years after pruning.

Table 6. Lumber recovery for Taiwania logs treated with various thinning and pruning regimens

Treatment	Lumber recovery (%)*
Thinning (T)	
Heavy	46.0
Medium	44.2
None	42.9
Pruning (P)	
Heavy	44.4
Medium	43.9
None	44.7
T × P	
AC	46.9a
AA	45.6a
AB	45.5a
BA	45.0a
BB	44.6a
CC	44.3a
BC	42.9a
CA	42.6a
CB	41.7a

*Means within a given category with the same letter (a) are not significantly ($P \leq 0.05$) different as determined by Duncan's multiple range test

Lumber recovery

The rates of lumber recovery were analyzed using ANOVA, which showed that the effects of thinning, pruning, and thinning plus pruning on lumber recovery of logs were not significant. Table 6 compares lumber recovery from logs treated with various thinning, pruning, and thinning plus pruning interaction regimens. The variations in lumber recovery from logs after thinning showed the following trend: heavy (46.0%) > medium (44.2%) > no

Table 7. Lumber recovery for Taiwania trees treated with various thinning and pruning regimens

Treatment	Lumber recovery (%)
Thinning (T)	
Heavy	31.1a
Medium	27.9a
None	24.1b
Pruning (P)	
Heavy	27.3a
Medium	28.8a
None	26.9a
T × P	
CA	19.8a
CC	25.2ab
AC	26.7b
CB	27.2b
BA	27.3b
BB	27.5b
BC	28.9bc
AB	31.8bc
AA	34.7c

(42.9%) thinning. This indicates that heavy thinning had higher lumber recovery than either medium or no thinning.

The relation between the log diameter and lumber recovery from logs was examined. The thinning intensity slightly enhanced lumber recovery of logs, but there were no significant differences among the various thinning intensities based on statistical analyses due to the narrow distribution of log sizes in this study.

In general, the overall conversion factor, volume yield, and output of sawmilling increased with increasing log diameter. In other words, lumber recovery is higher for logs with larger diameters.[3,21–26] However, in this study there was no significant difference in lumber recovery from logs with a narrow distribution of log sizes (log diameter classes).

The variations of lumber recovery from logs after pruning showed the following trend: no pruning (44.7%) > heavy pruning (44.4%) > medium pruning (43.9%). However, there was no significant difference in lumber recovery from logs after the thinning treatments. This finding was similar to those in the reports of Dwyer and Lowell,[16] Lowell and Dwyer,[17] and Cahill et al.,[27] which indicated that pruning did not affect the quantity of lumber output from scarlet oak, black oak, or Douglas fir logs. The variations in lumber recovery from logs after exposure to the thinning plus pruning interaction are also shown in Table 6.

The rates of lumber recovery were analyzed using ANOVA, which showed that the effects of thinning and the thinning plus pruning interaction on the lumber recovery from trees were significant. However, it was not statistically significantly affected by pruning. Lumber recovery after the various regimens of thinning, pruning, and thinning plus pruning are shown in Table 7. The variations in lumber recovery from trees after thinning showed the following trend: heavy (31.1%) > medium (27.9%) > no (24.1%) thinning. This indicates that heavy thinning produced higher lumber recovery than medium or no thinning.

In this study, the heavily thinned plots had a wider plantation than medium or not thinned plots. In general, a larger DBH is the result of a widely spaced plantation, which indicates that a larger DBH gives higher lumber recovery.

The relation between the DBH and lumber recovery of sample trees was examined. The lumber recovery values increased linearly with increasing DBH, although the R^2 was low (0.21; $P = 0.05$ on F-value test). This suggested that in even-age stands the trees with more rapid growth had a larger DBH, so they had higher lumber recovery. This finding was similar to that reported by Lowell and Dwyer,[17] who indicated that thinning did not affect the conversion ratio for scarlet oak or black oak logs and that thinning increased the amount of sawn lumber per tree owing to an increase in DBH.

The variations of lumber recovery from trees after pruning are shown in Table 7. There were no significant differences in lumber recovery from these trees based on the pruning treatments. The variations of lumber recovery after exposure to the thinning plus pruning interaction are also shown in Table 7. In conclusion, our results showed that higher lumber recovery from Taiwania trees occurred after thinning owing to an increase in DBH.

Conclusions

This study indicates that trees with heavy thinning had more knots (total and dead) than with medium or no thinning. Thus, pruning reduces the number of knots compared to those seen with no pruning. Heavy thinning produced larger-diameter knots than medium or no thinning; and pruning caused smaller-diameter knots compared to no pruning. The healing process of pruning wounds seemed to have not completely produced clear wood 9 years after the pruning.

The thinning intensity slightly promoted the lumber recovery of logs, whereas pruning did not affect lumber recovery of Taiwania trees or logs. Thinning increased the lumber recovery per tree owing to an increase in DBH.

Acknowledgments The authors thank the Taiwan Forestry Research Institute (TFRI) and the National Science Council of ROC for financial support through grants 91-AS-1.4.1.F-G1 and NSC 90-2313-B002-338, respectively. This paper is contribution No. 216 of the TFRI.

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