EVALUATION OF QUALITY OF JAPANESE CEDAR (*CRYPTOMERIA JAPONICA*) TREES GROWN UNDER DIFFERENT ROW THINNING TREATMENTS

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CHEN JH, WANG SY, LIN CJ, CHIU CM & TSAI MJ. 2014. Evaluation of quality of Japanese cedar (*Cryptomeria japonica*) trees grown under different row thinning treatments. The effects of various row thinning treatments on the wood quality of Japanese cedar (*Cryptomeria japonica*) using non-destructive techniques were investigated. Differences between row thinning treatments were not statistically significant. The earlywood density (ED), latewood density (LD), minimum density in a ring (D_{Min}), maximum density in a ring (D_{Max}) and latewood percentage (LWP) were the most important predictors of ring density (RD) according to simple linear regressions. Compressive strength in the transverse direction increased from the pith outwards to certain points (about 11–24 years old) and then gradually decreased towards the bark. The ring width and earlywood width in the transverse direction changed irregularly from the pith outwards to the 4th ring, then gradually decreased towards the 25th ring and then slowly increased towards the bark. However, the RD and LWP in the transverse direction changed irregularly from the pith outwards to the 4th ring, gradually increased towards the 25th ring and then decreased irregularly towards the bark.

Keywords: Non-destructive technique, ring characteristics, dynamic modulus of elasticity

INTRODUCTION

Under constraints of environmental protection and shortage of wood resources, plantation sites in Taiwan have to be managed as ecological system. The purpose is to develop three sustainable functions of ecology, society and economy. Therefore, evaluating the health and wood quality of trees in planted forests is very important. Protecting the ecosystem and restoring the original and high-valued timber of a natural Taiwan cypress plantation require a series of relevant new experiments and research. This is because plantations are planted in large numbers with Japanese cedar (*Cryptomeria japonica*) in the Chi-Lan mountainous area, north-eastern Taiwan. One possible method is strip and row thinning treatments, a low-disturbance treatment to sustain the environment, which can help build multi-storeyed stands (Lo-Cho et al. 1997). There is no relevant study at present on effects of different widths of row thinning treatments on quality of Japanese cedar wood.

There are many advantages of obtaining information on tree quality during tree growth and the key technique for evaluating this is non-destructive techniques (NDTs) (Chiu et al. 2004). Wood scientists have been using NDTs to determine wood quality and evaluate tree quality (Wang et al. 2001, Wang et al. 2005). Low cost, easily operated and efficient techniques such as ultrasonic waves are useful tools for evaluating physical properties of wood. Relationships between NDT parameters and wood density or machine strength have been established (Pellerin & Ross 2002, Ross et al. 2005, Wang et al. 2005). Research also shows that dynamic modulus of elasticity of wood and static modulus of elasticity have positive significant relationships (Wang et al. 2001, Emerson et al. 2002, Leichti et al. 2005).

The Pilodyn which inserts a probe into the wood is an economic, portable, easily used and commercial NDT. A strong relationship between penetration depth and wood density can be obtained. This technique has been used to test the residual strength of wooden utility poles (Smith & Morrell 1989). The Pilodyn can also be used to select trees for thinning or to evaluate wood quality (Rozenberg & de Sype 1996, Jacques et al. 2004).

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The fractometer, which is used to test longitudinal compressive strength of a 5-mm-diameter increment core is a faster, easier operated technique. The fractometer is used to evaluate compressive strength and monitor wood quality (Kasal 2003, Mattheck & Breloer 2003, Lin et al. 2004). X-ray is also used to analyse annual rings for studying tree-ring climatology (Bucur et al. 1997, Koga & Zhang 2002).

The purpose of this study was to evaluate the quality of Japanese cedar trees grown under different row thinning treatments using ultrasonic wave, fractometer, Pilodyn and X-ray scan techniques. The results could provide important information for forestry management, silvicultural practices and wood utilisation in terms of wood quality.

MATERIALS AND METHODS

Plantation site

The study site was located in Compartment No. 20, Tai-Ping-Shan Working Circle of the Forestry Development Department of the Veterans Affairs Commission. The site has an average elevation of 1100 m. The land gradient is between 15 and 35°. The mean annual temperature near the Yuan-Yang Lake Nature Reserve of Chi-Lan-Shan was 13 °C, and the mean annual relative humidity was 89% between 1994 and 1996. The total precipitation in 1994 was 4066 mm (Lo-Cho et al. 1997).

Experimental design

Japanese cedar was planted with a spacing of 2 m × 1.5 m in 1966. The different row thinning treatments for Japanese cedar stands are shown in Table 1. Four row thinning treatments were implemented at a stocking rate of 1900 trees ha^{-1} in 1990, when the trees were 24 years old. In this study, there were four row thinning treatments and a control (no thinning) as follows:

Type A: area without thinning treatment as control area (no treatment)
Type B: row thinning by strip cutting of two rows (width of the cut strip was 6 m)
Type C: row thinning by strip cutting of three rows (width of the cut strip was 8 m)
Type D: row thinning by strip cutting of four rows (width of the cut strip was 10 m)
Type E: row thinning by strip cutting of five rows (width of the cut strip was 12 m)

The area, about 3.6 ha, was divided into 15 smaller plots (five treatments × three replicates), each 0.24 ha (120 m × 20 m) including the buffer strips. The diameter and height of each tree on the 15 small plots were studied. Five similar diameter trees were selected from each plot. A total of 75 trees were explored using ultrasonic waves, fractometer, Pilodyn and X-ray scan techniques.

Table 1 Structure of different row thinning treatments of *Cryptomeria* stands

Treatment/ width of cut strip	Age (years)	Mean dbh (cm)	Mean height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Density (trees ha^{-1})	Mortality (%)
No treatment	24	19.6	15.6	44.1	326.4	1387	
	36	23.2	18.5	52.2	453.4	1153	16.9
6 m							
After treatment	24	21.0	16.0	25.5	202.3	611	
After 12 years	36	27.8	18.0	31.2	265.4	486	21.1
8 m							
After treatment	24	20.6	16.0	21.5	161.2	616	
After 12 years	36	28.3	18.1	30.0	259.1	454	25.5
10 m							
After treatment	24	20.0	15.8	18.9	140.9	577	
After 12 years	36	27.4	17.9	26.8	228.5	428	26.8
12 m							
After treatment	24	19.5	15.6	24.0	177.0	769	
After 12 years	36	25.9	17.5	32.6	250.7	493	35.1

Dbh = diameter at breast height

Ultrasonic wave method

Standing trees were analysed using ultrasonic wave technique for longitudinal and radial transmission. The ultrasonic wave apparatus (frequency 22 kHz) used transmitting and receiving transducers.

The ultrasonic wave apparatus was used to explore the longitudinal length of 50 cm from the diameter at breast height (dbh) position (1.3 m above the ground) to 80 cm above the ground and the virtual radial (180°) direction in the dbh position in January 2006 when the trees were about 40 years old. The ultrasonic wave velocity (V) and the dynamic modulus of elasticity (DMOE) were calculated from the following formulae:

$$V = L/T \quad (\mathrm{m\ s^{-1}}) \qquad (1)$$

and

$$\mathrm{DMOE} = V^2 \times D \quad (\mathrm{MPa}) \qquad (2)$$

where L = distance between two transducers, T = propagation time of the pulse from the transmitting transducer to the receiving transducer and D = density of wood.

Pilodyn test

The Pilodyn is usually used to evaluate the penetration depth of wood by a striker pin at stable energy of 6 J. The probe in this study was 3 mm in diameter and 4 cm in length and was used to probe wood at dbh position without the bark. It was used on the tangential face of the trees, so its penetrating direction was radial. The penetration depth (mm) was recorded and the average penetration depth of each tree was calculated.

Fractometer method

From the eastern direction of each tree, two pith-to-bark increment core specimens (5 mm in diameter) were extracted at the breast height position (same direction) for the fractometer measurement and X-ray scanning. Measurements were made on conditioned cores (12% moisture content) and a fractometer was used to evaluate the longitudinal compressive strength of incremental cores from the pith to the bark at 0.6 cm sections.

X-ray scanning and ring characteristics

The ring characteristics of extracted (distilled water and alcohol–benzene) and conditioned strips were analysed by a tree-ring analyser. The strips were scanned in the radial direction.

Dimensions of the standard collimator were 0.038 mm wide and 1.59 mm high at the detector. The increment of the sample step size was 0.02 mm. The determination of density was based on the relationship of X-ray attenuation and density (QMS 1999).

Each type had three sites and each site had five sample trees. Each tree had two cores. The absorption of X-rays was determined in a controlled energy range. This was related to the actual sample density (12% moisture). The following characteristics were derived: average ring width (RW), earlywood width (EW), latewood width (LW), ring density (RD), earlywood density (ED), latewood density (LD), density, maximum density in a ring (D_{Max}), minimum density in a ring (D_{Min}) and latewood percentage in a ring (LWP) across the sample.

Growth rate of different row thinning treatments is

$$GR = \sum_{i=1}^{n} RW_n^2 \pi - \sum_{i=1}^{n-1} RW_{n-1}^2 \pi$$

where GR = growth rate, RW = ring width, and i and n = number of trees.

RESULTS AND DISCUSSION

Dynamic modulus of elasticity and longitudinal compression strength

The ultrasonic wave velocity, dynamic modulus of elasticity and compression strength of standing trees treated with different row thinning treatments are shown in Table 2. No apparent difference existed according to analysis of variance (ANOVA). Different row thinning treatments did not affect the tested parameters of Japanese cedar. The average longitudinal ultrasonic wave velocity was 2628.1–2878.9 m s^{-1}, average longitudinal dynamic modulus of elasticity was 3306.3–4358.2 MPa, average radial ultrasonic wave velocity was 1477.0–1642.8 m s^{-1}, average radial dynamic modulus of elasticity was 1053.0–1363.3 MPa, average longitudinal compression strength was 33.0–38.6 MPa and penetration depth with the Pilodyn was 16.1–20.1 mm. The average radial

Table 2 Dynamic modulus of elasticity and compressive strength of standing trees obtained from different row thinning treatments

Parameter	Treatment (width of cut strip)				
	No	6 m	8 m	10 m	12 m
Vl (m s^{-1})	2865.1	2878.9	2628.1	2652.5	2665.0
DMOEl (MPa)	4167.4	4358.2	3306.3	3432.2	3857.1
Vr (m s^{-1})	1512.2	1642.8	1559.4	1477.0	1571.1
DMOEr (MPa)	1151.0	1363.3	1165.4	1053.0	1327.0
Fc (MPa)	38.6	35.0	35.9	33.0	33.3
P (mm)	20.1	17.3	16.3	16.1	16.3

Vl = ultrasonic wave velocity parallel to the grain (longitudinal), DMOEl = longitudinal dynamic modulus of elasticity, Vr = ultrasonic wave velocity perpendicular to the grain (radial), DMOEr = radial dynamic modulus of elasticity, Fc = compressive strength parallel to grain, P = penetration depth

ultrasonic wave velocity of Taiwan incense cedar (*Calocedrus formosana*) was 1393–1656 m s^{-1} (Chiu et al. 2013).

Ring characteristics

Nine ring characteristics of standing trees obtained from different row thinning treatments are shown in Table 3. There was no significant difference according to ANOVA. Therefore, different row thinning strengths did not affect the nine ring characteristics of Japanese cedar. The average width of annual rings (RW) was 2.02–3.26 mm, average width of earlywood (EW) was 1.42–2.33 mm, average width of latewood (LW) was 0.61–1.05 mm, average density of annual rings (RD) was 478.1–586.5 kg m^{-3}, average density of earlywood (ED) was 320.0–398.9 kg m^{-3}, average density of latewood (LD) was 837.8–961.9 kg m^{-3}, average highest density (D_{Max}) was 964.3–1120.2 kg m^{-3}, average lowest density (D_{Min}) was 212.5–246.7 kg m^{-3} and latewood percentage (LWP) was 31.2–35.5%.

Relationships between the nine ring characteristics

There were positive significant relations of RW with EW and LW (Table 4). The r of 0.98 between RW and EW was higher than that of 0.45 between RW and LW indicating that EW strongly affected RW. There were significant negative relationships between LWP and RW as well as between LWP and EW with r values of -0.41 and -0.55. However, positive significant relationship between LWP and LW was found with r of 0.42.

The ED, LD, D_{Min}, D_{Max} and LWP had positive significant relations with RD (r = 0.44–0.68). This showed that ED, LD, D_{Min}, D_{Max} and LWP were the most important predictors of RD. There were also positive significant relationships between ED and D_{Min} as well as between LD and D_{Max}. There was weak relationship between RW and wood density. Lin et al. (2012) reported that RW and RD had weak relationship.

Growth rate in different row thinning treatments

Before row thinning, all sites had similar growth rates (Table 5 and Figure 1). The average growth rate was about 7.48 to 9.65 mm^2 $year^{-1}$. After row thinning, the growth rates of all thinning sites were significantly faster than the control site. The average growth rate of row thinning sites was 16.85 to 19.32 mm^2 $year^{-1}$ and the average growth rate of control site was 9.48 mm^2 $year^{-1}$. Compared with before and after, the after growth rate of control site was 1.27 times higher than before. However, the ratio of after/before for treatment sites was over 2 times. A jack pine tree of 150 mm dbh showed 33% increase in annual ring width following heavy thinning (Schneider 2007). Meanwhile Duchesne and Swift (2008) reported a 37% increase in dbh 31 years after heavy thinning. There was significant and positive effect on annual radial growth for heavy thinning (one of three rows removed) but not for light thinning (one of four rows removed) (Tong et al. 2011). Growth rate ratios of dbh in moderately- and heavily-thinned stands were 1.07 and 1.30 respectively (Serdar & Yılmaz 2009). Tree height and tree volume

Table 3 Ring characteristics of standing trees obtained from different row thinning treatments

Parameter	Treatment (width of cut strip)				
	No	6 m	8 m	10 m	12 m
Width (mm)					
Ring	2.02	3.12	3.26	3.13	3.23
Earlywood	1.42	2.20	2.33	2.20	2.18
Latewood	0.61	0.92	0.94	0.92	1.05
Density (kg m^{-3})					
Ring	478.1	543.9	509.4	509.4	586.5
Earlywood	320.0	353.3	361.1	351.8	398.9
Latewood	837.8	961.9	838.7	864.0	936.6
Highest	977.6	1120.2	964.3	997.5	1089.7
Lowest	213.5	233.5	222.0	212.5	246.7
Latewood percentage (%)	31.8	31.6	31.2	32.1	35.5

Table 4 Coefficients of correlation between ring characteristics

Variable	RW	EW	LW	RD	ED	LD	D_{Min}	D_{Max}	LWP
RW									
EW	**0.98****								
LW	**0.45****	0.24**							
RD	-0.24**	-0.32**	0.24**						
ED	0.18**	0.18**	0.08**	**0.59****					
LD	-0.19**	-0.14**	-0.25**	**0.44****	0.15**				
D_{Min}	0.01 ns	0.01 ns	0.03 ns	**0.51****	**0.72****	0.14**			
D_{Max}	-0.14**	-0.13**	-0.08**	**0.44****	0.08**	**0.90****	0.09**		
LWP	**-0.41****	**-0.55****	**0.42****	**0.68****	0.01 ns	-0.04*	0.14**	0.05*	

** Significantly different at the 1% level ($p < 0.01$); * significantly different at the 5% level ($p < 0.05$); ns = not significant ($p > 0.05$); RW = average ring width, EW = average earlywood width, LW = average latewood width, RD = average density of ring, ED = average earlywood density, LD = average latewood density, D_{Min} = average lowest density in a ring, D_{Max} = average highest density in a ring, LWP = average latewood percentage

growth rates were 0.97 and 1.06 for moderately thinned, and 1.23 and 1.64 for heavily-thinned plots respectively (Serdar & Yılmaz 2009). The largest values for the mean tree were observed with the heaviest thinning treatment.

Variations in compressive strength in transverse direction

Compressive strength in the transverse direction increased from the pith outwards to a certain point (84 mm) and then gradually decreased towards the bark (Figure 2). The trend was similar to that reported by Wang and Chiu (1993), who showed that the minimum value of compressive strength of Japanese cedar occurred near the pith and increased radially outwards reaching a maximum at about 6–8 cm from the pith, then decreasing towards the bark. According to the relationship between ring number and distance from the pith (Figure 3), the year of the wood could be calculated by the distance from the pith. Using a statistical formula, the wood was about 11–24 years old when Japanese cedar was considered juvenile wood. Chen (1991) reported that the mature age of Japanese cedar in different plantation densities was 18–19.7 years. Csoka et al. (2005) indicted that mature wood of Japanese cedar was 21 years old.

Table 5 Growth rate in different row thinning treatments

Treatment (width of cut strip)	Before thinning (mm^2 $year^{-1}$)	After thinning (mm^2 $year^{-1}$)	After/before thinning
No	7.48 ± 5.76 a	9.48 ± 13.25 b, y	1.27
6 m	7.58 ± 4.97 a	16.85 ± 5.97 b, x	2.22
8 m	8.71 ± 5.21 a	18.93 ± 9.72 b, x	2.17
10 m	9.65 ± 6.56 a	19.32 ± 12.31 b, x	2.00
12 m	8.85 ± 6.34 a	18.22 ± 18.42 b, x	2.06

Different letters (a and b, x and y) in a row indicate significant differences at the 0.05 level by ANOVA and Tukey's test

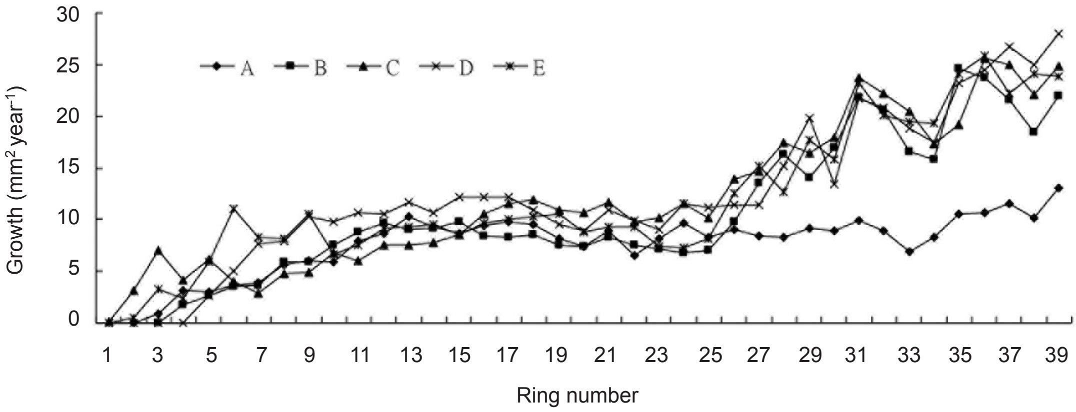

Figure 1 The growth rates of Japanese cedar; A = no thinning treatment, B = width of cut strip 6 m, C = width of cut strip 8 m, D = width of cut strip 10 m, E = width of cut strip 12 m

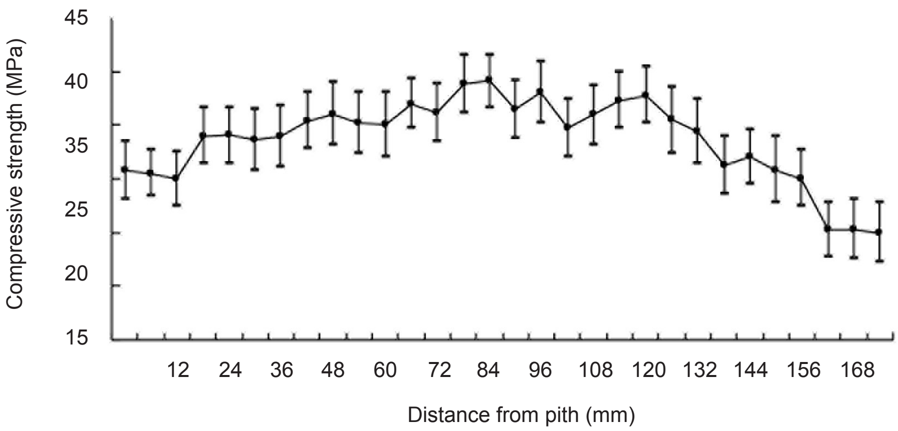

Figure 2 Transverse variation in average compressive strength; bars represent 95% confidence interval

Variations of ring characteristics in transverse direction

The transverse variations in RW, EW and LW are shown in Figure 4. RW and EW in the transverse direction changed irregularly from the pith outwards to the 4th ring, then gradually decreased towards the 25th ring and then slowly increased towards the bark. The trend was similar to that reported by Wang and Chen (1992). LW increased to the 2nd year and then gradually decreased towards the bark. Beyond the age of 25 years, RW and EW increased a little, which might have been affected by low-intensity thinning. However, there was almost no effect on LW. RW and RD of trees seemed to increase

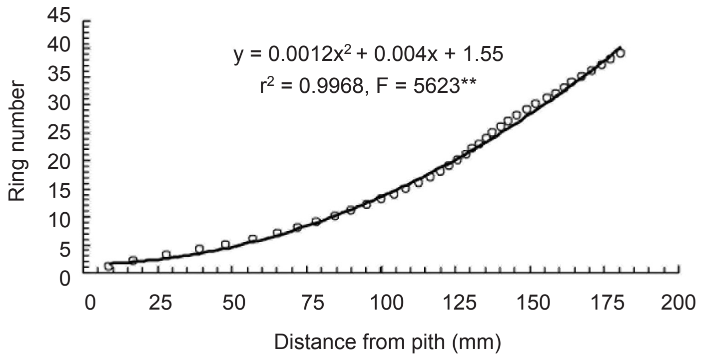

Figure 3 Relationship between ring number and distance from the pith

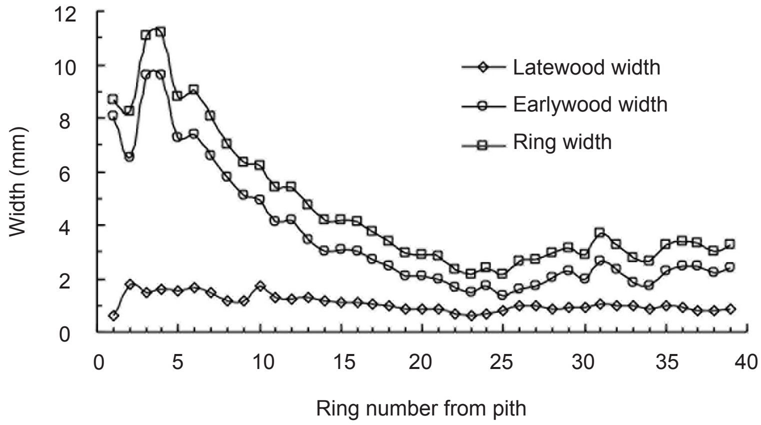

Figure 4 Mean transverse variations in the widths of ring, earlywood and latewood

after thinning compared with those trees grown with an unthinned regime in the Chilan Mount (Lin et al. 2012).

D_{Max} and LD in the transverse direction changed irregularly from the pith outwards to the 4th ring and then gradually increased towards the bark (Figure 5). ED and D_{Min} changed irregularly from the pith outwards to the 4th ring and then gradually decreased towards the bark. RD (Figures 5) and LWP (Figure 6) changed irregularly from the pith outwards to the 4th ring, then gradually increased towards the 25th ring and then decreased irregularly towards the bark. The results corresponded with those reported by Wang and Chen (1992).

CONCLUSIONS

There was no significant difference between ultrasonic wave velocity in the longitudinal and transverse directions, dynamic modulus of elasticity in the longitudinal and transverse directions, longitudinal compressive strength and the penetration depth of the Pilodyn of Japanese cedar trees obtained from different row thinning treatments. There were positive significant relationships of RW with EW and LW. There were negative significant relationships of LWP with RW and EW. However, a positive significant relation between LWP and LW was found. For growth rate, the value of after row thinning was bigger than before, about two times. There were positive significant relationships for RD with LD, ED, D_{Min}, D_{Max} and LWP. There were positive significant relationships of ED with D_{Min} and of LD with D_{Max} with regard to ring characteristics. RW and EW changed irregularly in the transverse direction from the pith outwards to the 4th ring, then gradually decreased towards the 25th ring and then slowly increased towards the bark. RD and LWP changed irregularly from the pith outwards to the 4th ring, then gradually increased towards the 25th ring and then decreased irregularly towards the bark.

There were no differences in wood properties as measured by non-destructive test. Thus, the

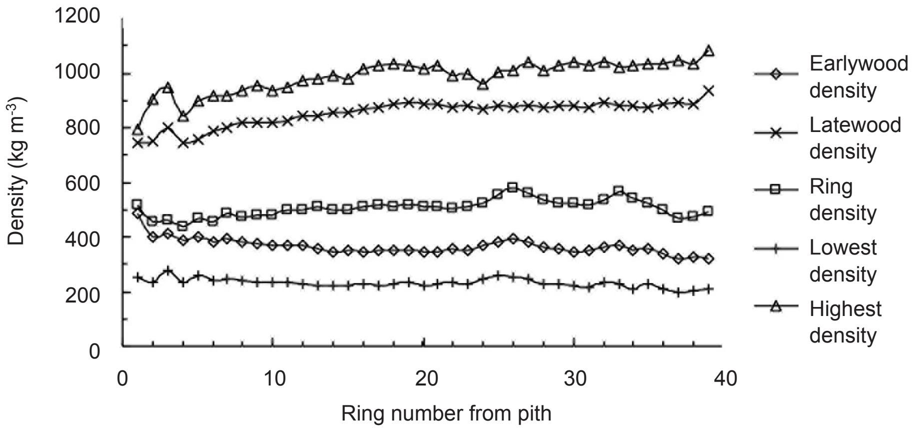

Figure 5 Mean transverse variations in the ring, earlywood and latewood densities

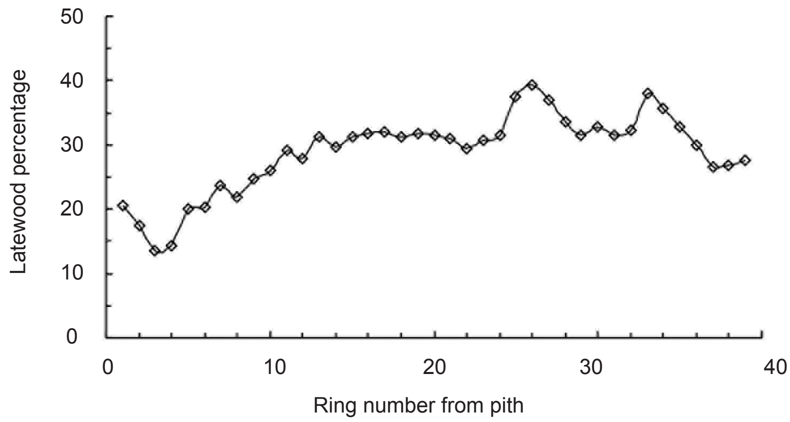

Figure 6 Mean transverse variation in latewood percentage

key point for choosing the best row thinning treatment was growth rate. When the growth rate is better, wood volume will be more. Row thinning treatment promoted growth rate but did not affect wood properties.

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