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Full Length Research Paper

Ring characteristics of 95-year old Japanese cedar plantation trees grown in Taiwan

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The ring characteristics of 95 year old Japanese cedar plantation trees grown in Taiwan were explored. Significant differences in the average ring width (RW), earlywood width, latewood width, ring density (RD), earlywood density, latewood density, highest density, lowest density, and latewood percentage were observed among three tree diameter classes and three radial stages of ring numbers. The RW parameters in the radial direction increased from the pith outward to the fifth ring number, and then decreased between about the 20th to 30th ring number. Finally, it was almost constantly sustained toward the bark side. The RD in the radial direction slowly decreased from the pith outward to the bark side. Wider tree rings and higher density are associated with juvenile wood close to the pith and narrower tree rings and lower density are typical for mature wood outward to the bark side. The RD in the intermediate tree was higher than in the dominant and overtopped trees; however, the RW in the intermediate tree was not narrower than in the dominant and overtopped trees. The RW did not correlate with the RD.

Key words: Japanese cedar (*Cryptomeria japonica*), plantation trees, ring characteristics.

INTRODUCTION

Japanese cedar (*Cryptomeria japonica* D Don.) is a dominant species in plantations and is a potentially important timber resource in Taiwan. Japanese cedar is of major economic importance in the timber industry because of the quality of its wood products and growth rate. During the past several decades, the plantation area has increased rapidly. This type of tree is easy to plant with a high growth rate and survival ratio. However, the utilization and processing of medium or small logs (short rotation management) has encountered some difficulties and questions. Most studies have focused on young Japanese cedar trees in Taiwan (Wang and Chen, 1992; Ishiguri et al., 2005; Aiura, 2006; Tsushima et al., 2006; Lin et al., 2008; Wang et al., 2008) and a few have concentrated on aged trees in Japan (Csoka et al., 2005; Zhu et al., 2005). Large timber could be raised and managed on a long rotation to encourage application and enhance wood value. Forest managers and wood industries would benefit from understanding the tree growth and wood properties of aged Japanese cedar trees.

Japanese cedar originated in Japan and the breeds are very wide. Nine types of Japanese cedar can be found in Xitou Tract, the Experimental Forest of National Taiwan University, including Yoshino, Satsuma, Akita, Kumano, Ayayanagi, Itadani Red, Itadani Black, Sato, and Shiitada. The Yoshino Japanese Cedar has the dominant population here since its living environment in Japan is similar to that of the central mountains in Taiwan. However, since the plantation sites and climate of Japan and Taiwan are still different, the tree growth (ring width) and wood quality (ring density) of Japanese cedars growing in Taiwan may need to be clarified.

During the investigation of tree growth performance in different experimental plots, an interesting large Japanese cedar plantation timber was observed. We

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wanted to comprehend the radial variation in tree growth and wood quality of aged trees. The "Nishikawa Japanese Cedar" is the oldest plantation in Taiwan. It was introduced by Mr. Nishikawa, the first director of the Experimental Forest, Tokyo Imperial University, from Kawakami village, Yoshino River, Nara in 1912. When the Japanese cedar plantation trees planted as an aged large diameter class trees in long rotation management, the wood quality should be understood for forest management and utilization in Taiwan. We therefore hoped to understand the tree ring width and ring density of aged Japanese cedar plantation trees grown in Taiwan.

Tree ring analysis is widely applied for many purposes. Ring characteristics (ring width, ring density, etc.) are useful indicators in forest management and product manufacturing because they are strongly correlated with many other traits, such as tree diameter growth and wood strength properties (Zobel and van Buijtenen, 1989; Alteyrac et al., 2006). The purpose of this study was to explore the ring characteristics of 95-year old Japanese cedar plantation trees grown in Taiwan. Ring width and ring density information can facilitate tree growth and wood quality in forest management and wood utilization.

MATERIALS AND METHODS

Condition of experimental forest site

The sample trees in the study were from the 6th compartment (E120°47´, N23°40´), Xitou Tract, in the Experimental Forest of National Taiwan University. The site elevation is about 1,100 m. The annual average temperature is 17°C and the highest and lowest temperatures are 21 and 12°C each year, respectively. The annual average precipitation is about 2,900 mm, with 80% of it concentrated from May to September every year. The site is plain, and the topsoil is pretty thick with moderate adherence and moisture. Xitou area is mostly geological layers of the third century, sandstone and sandy shale layer overlap from status, and mostly sandy soil (Wang et al. 2006).

Japanese cedar forest and sampled specimens

The experimental site was planted in 1912 (established in 1926) and the plantings (sampled in 2008) are about 95 years old. The initial plantation density of the experimental sites was 2100 trees/ha without any thinning or pruning practice during the past 95 years, hence, the density changed naturally owing to decline or disease. The area of this study site is about 2 ha and a total of 14 sampled trees with different diameter size (normal distribution) were selected according to growth investigation. An increment corer was used to cut cores 5 mm in diameter from sample trees. From the eastern aspect of each sample tree, we extracted a bark-to-pith-to-bark increment core specimen at a position of DBH (same direction) in October 2008, when the specimens were about 95-years-old. All core specimens were mounted and processed into slices for x-ray densitometric scanning (Schweingruber, 1989; Koga and Zhang, 2004; Knapic et al. 2007).

Analysis of x-ray tree ring characteristics

Ring width and density parameters can be explored by x-ray densitometric techniques. An x-ray densitometric technique was used on the slices (cores) to determine the ring characteristics.

Volatiles of the slices were extracted using distilled water and an alcohol-benzene solution. The conditioned slices were subjected to a direct-reading x-ray densitometer (commercial device, QTRS-01X Tree Ring Analyzer, Quintek Measurement Systems (QMS), Knoxville, TN, USA) for ring characteristics. Each slice (about at a 12% MC) was scanned and moved through the x-ray machine in the radial direction.

The main case of the QTRS-01X contains both an x-ray source and a high-voltage power supply (25,000 V). The standard collimator supplied with the QTRS-01X analyzer measures approximately 0.038 mm in width and 1.59 mm in height at the detector. The sample step size can be adjusted at increments of 0.02-mm. The determination of density by the QTRS-01X scanning system is based on the relationship between x-ray attenuation and density (QMS, 1999).

The Tree Ring Analyzer actually determines the absorption of radiation from a collimated beam of x-rays of a narrowly controlled energy range. That absorption is related to the actual sample density by basic radiation attenuation principles. The ring density boundary was identified by a fixed density threshold. Based on the density profiles, the earlywood/latewood boundary in each ring was defined by an average of both the maximum (Dmax) and minimum density (Dmin) in the ring. Therefore, the density profile and ring characteristics were confirmed and determined with a tree-ring analysis program (attached to the QMS). The ring characteristics included the average tree ring width (RW), earlywood width (EW), latewood width (LW), tree ring density (RD), earlywood density (ED), latewood density (LD), Dmax, Dmin, and latewood percentage (LWP) in rings across the sample. All specimens reached moisture contents of approximately 12% and the wood density value (weight at 12% MC/volume at 12% MC) was adopted when the ring density components were converted from the degree of x-ray absorption.

Statistical analysis

For understanding effects of tree sizes and cambium ages on ring characteristics, all 14 sampled trees can be classified into three groups based on the DBH sizes of individual trees, namely, Tree A (from 441.4 to 458.3 mm, 4 trees), Tree B (from 386.3 to 434.3 mm, 6 trees), and Tree C (from 341.3 to 385.2 mm, 4 trees). Moreover, all ring numbers were separated among the three groups by radial positions at breast height, namely, Ring A (from the first outward to the 20th ring number) and Ring B (from 21st outward to the 50th ring number), and Ring C (from 51st ring number outward to the bark side). The average tree ring characteristics were expressed by descriptive statistics. An analysis of variance (ANOVA) was used to determine if the DBH (Tree A, B, and C) and radial (Ring A, B, and C) levels significantly affected ring characteristics by SPSS software. F values were computed to test for the significance of levels. When the level effects were significant, means were compared using Tukey test.

RESULTS

Ring width components

The differences in average RW, EW, and LW among the three DBH groups were analyzed using the analysis of variance (ANOVA) (Table 1). Significant differences in the RW components were observed between the three DBH groups. A comparison of the average RW components of

Table 1. Results of analysis of variance (ANOVA) tests for differences in the ring characteristics between three DBH classes of Japanese cedar tree.

Variables		**Sum of squares**	**Degree of freedoms**	**Mean square**	**F ratio**
RW	Between groups	50.9	2	25.4	3.1*
	Within groups	19073.8	2314	8.2	
	Total	19124.7	2316		
EW	Between groups	49.0	2	24.5	4.1*
	Within groups	13970.3	2314	6.0	
	Total	14019.2	2316		
LW	Between groups	3.2	2	1.6	4.2*
	Within groups	887.5	2314	0.4	
	Total	890.7	2316		
RD	Between groups	416885.3	2	208442.7	21.4**
	Within groups	22539036.4	2314	9740.3	
	Total	22955921.8	2316		
ED	Between groups	55369.8	2	27684.9	7.1**
	Within groups	8991974.1	2314	3885.9	
	Total	9047343.9	2316		
LD	Between groups	822533.1	2	411266.6	21.2**
	Within groups	44896845.6	2314	19402.3	
	Total	45719378.7	2316		
Dmin	Between groups	57361.8	2	28680.9	9.8**
	Within groups	6802950.2	2314	2939.9	
	Total	6860312.0	2316		
Dmax	Between groups	244329.5	2	122164.7	3.3*
	Within groups	84715990.3	2314	36610.2	
	Total	84960319.8	2316		
LWP	Between groups	6530.2	2	3265.1	24.9**
	Within groups	303501.1	2314	131.2	
	Total	310031.3	2316		

EW, earlywood width; LW, latewood width; RW, ring width; ED, earlywood density; LD, latewood density; RD, ring density; Dmin, minimum density in a ring; Dmax, maximum density in a ring; LWP, Latewood percentage. Japanese cedar trees can be classified into three classes on the basis of diameter at breast height (DBH), namely, Tree A (from 441.4 to 458.3 mm, 4 trees), Tree B (from 386.3 to 434.3 mm, 6 trees), and Tree C (from 341.3 to 385.2 mm, 4 trees). * and **, Significant at the 5% and 1% level by the F-test.

aged Japanese cedar trees is shown in Table 2. According to the Tukey test, the average RW and EW values in Tree A were significantly wider than those in Tree C (2.58 versus 2.04 and 2.21 versus 1.66 mm). The average RWs of Trees A and B, and Trees B and C did not differ significantly. However, the average LW in the Tree B was significantly wider than that in Tree A (0.62 versus 0.54 mm). All sampled trees can be classified into three groups based on the DBH sizes of individual trees, namely, dominant (Tree A), intermediate (Tree B), overtopped trees (Tree C). Therefore, specimens of dominant tree had larger RW than that of overtopped trees. Moreover, the RW in the intermediate tree was not narrower than in the dominant and overtopped trees.

The differences in average RW, EW, and LW among the three radial positions were analyzed using ANOVA (Table 3). Significant differences in the RW components were observed between the three radial positions. The

Table 2. Comparison of the average ring characteristics according to the three tree DBH classes.

Variables	Tree A	Tree B	Tree C
RW	2.58^{a}	2.49^{ab}	2.21^{b}
EW	2.04^{a}	1.87^{ab}	1.66^{b}
LW	0.54^{a}	0.62^{b}	0.55^{ab}
RD	378.5^{a}	410.6^{b}	398.2^{c}
ED	273.4^{a}	285.1^{b}	280.3^{ab}
LD	710.5^{a}	720.4^{a}	675.4^{b}
Dmin	205.0^{a}	208.0^{a}	217.4^{b}
Dmax	830.3^{ab}	837.9^{a}	812.3^{b}
LWP	23.4^{a}	27.1^{b}	27.1^{b}

Abbreviations are explained in the footnotes to Table 1. Means within a given row with the same letter do not significantly differ ($p \leqq 0.05$), as determined by Tukey test.

Table 3. Results of analysis of variance (ANOVA) for differences in the ring characteristics between three radial positions.

Variables		Sum of squares	Degree of freedoms	Mean square	F ratio
RW	Between groups	8328.3	2	4164.2	892.5**
	Within groups	10796.3	2314	4.7	
	Total	19124.7	2316		
EW	Between groups	5489.6	2	2744.8	744.6**
	Within groups	8529.7	2314	3.7	
	Total	14019.2	2316		
LW	Between groups	295.7	2	147.8	574.9**
	Within groups	595.1	2314	0.3	
	Total	890.7	2316		
RD	Between groups	761735.4	2	380867.7	39.7**
	Within groups	22194186.4	2314	9591.3	
	Total	22955921.8	2316		
ED	Between groups	833912.5	2	416956.2	117.5**
	Within groups	8213431.4	2314	3549.5	
	Total	9047343.9	2316		
LD	Between groups	1782293.9	2	891147.0	46.9**
	Within groups	43937084.8	2314	18987.5	
	Total	45719378.7	2316		
Dmin	Between groups	322400.8	2	161200.4	57.1**
	Within groups	6537911.1	2314	2825.4	
	Total	6860312.0	2316		
Dmax	Between groups	6859515.3	2	3429757.6	101.6**
	Within groups	78100804.5	2314	33751.4	
	Total	84960319.8	2316		
LWP	Between groups	4712.8	2	2356.4	17.9**
	Within groups	305318.5	2314	131.9	
	Total	310031.3	2316		

Abbreviations are explained in the footnotes to Table 1. Three radial sections of the core were separated by position: Ring A, from the first outward to the 20th ring number, Ring B, from the 21st outward to the 50th ring number, and Ring C, from the 51st outward to the bark side at breast height. **, Significant at the 1% level by the F-test.

Table 4. Comparison of the average ring characteristics according to the three radial positions at breast height.

Variables	Ring A	Ring B	Ring C
RW	6.13^{a}	1.66^{b}	1.31^{c}
EW	4.87^{a}	1.21^{b}	0.97^{b}
LW	1.26^{a}	0.46^{b}	0.34^{c}
RD	415.5^{a}	411.9^{a}	376.7^{b}
ED	313.4^{a}	281.9^{b}	262.8^{c}
LD	728.6^{a}	729.0^{a}	672.8^{b}
Dmin	228.3^{a}	213.6^{b}	197.7^{c}
Dmax	900.7^{a}	857.8^{b}	768.1^{c}
LWP	23.5^{a}	27.5^{b}	25.9^{c}

Abbreviations are explained in the footnotes to Table 1. Means within a given row with the same letter do not significantly differ ($p \leqq 0.05$), as determined by Tukey test.

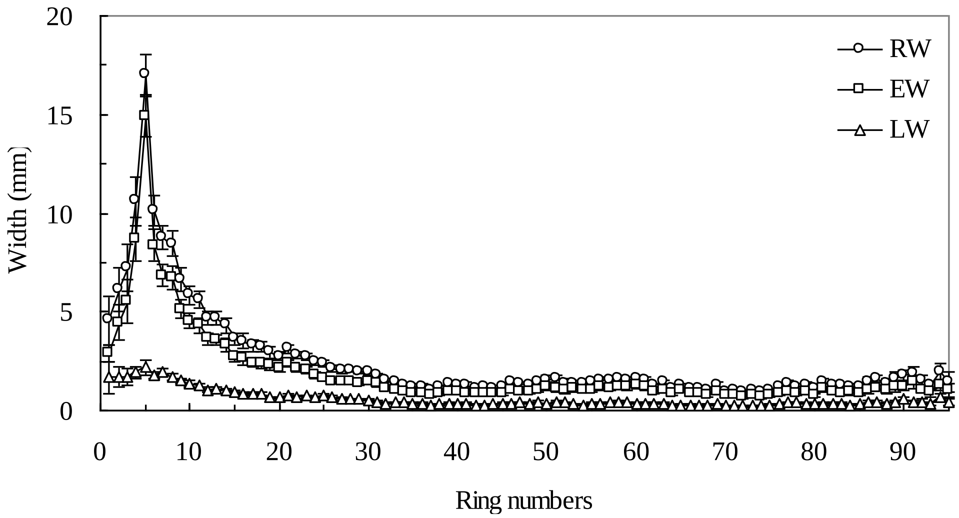

Figure 1. Inter-ring variation in ring width components based on all rings at breast height of all sampled Taiwan yellow cypress trees. Abbreviations are explained in the footnotes to Table 1.

average RW and LW values showed a trend as follows: Ring A > Ring B > Ring C by Tukey test (Table 3). However, the average EW in Ring A was significantly wider than those in the Rings B and C by Tukey test (4.87 versus 1.21 and 0.97 mm) (Table 4). All rings in the radial position were also separated into three zones, namely, juvenile, transition, and mature zones. Variations in average RW of the three zones showed the following trend: juvenile > transition > mature zones. Wider tree rings are associated with juvenile wood close to the pith, whereas narrower tree rings are typical for mature wood toward the bark.

Inter-ring variation in ring width components of Japanese cedar trees is shown in Figure 1. The RW parameters in the radial direction increased from the pith outward to about the fifth ring number, and then decreased at about the 20th to 30th ring number. Finally, it was almost constantly sustained or lightly decreased toward the bark side. Transition between juvenile and mature wood as determined by visual interpretation of graphically plotted radial variation in ring width was at about the 20th to 30th ring numbers from the pith. Thus, the juvenile-mature wood demarcation was at about 20th to 30th ring number from pith.

From the above results in this study, the specimens of Tree A (dominant tree) and Ring A (juvenile wood) had wider ring width than those of Tree C (overtopped tree) and Rings B and C (mature wood, and Rings B > C), respectively.

Ring density components

The differences in average RD, ED, LD, Dmin, and Dmax

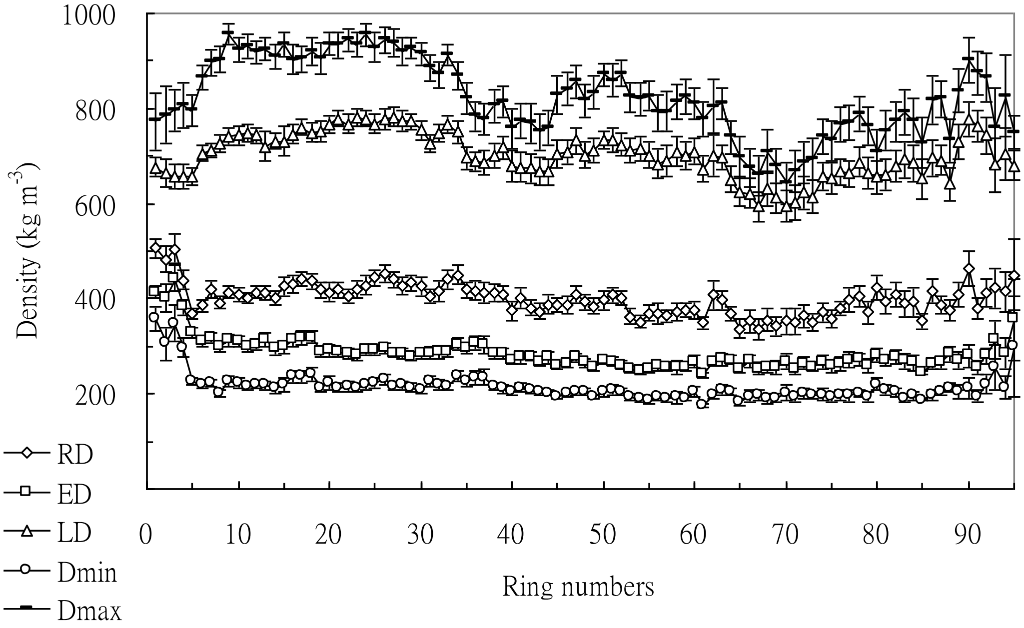

Figure 2. Inter-ring variation in ring density components based on all rings at breast height of all sampled Taiwan yellow cypress trees. Abbreviations are explained in the footnotes to Table 1.

among the three DBH groups were analyzed using ANOVA (Table 1). Significant differences in the RD components were observed between the three DBH groups. A comparison of the average RD components of aged Japanese cedar trees is shown in Table 2. The average RD value showed the following trend: Tree B > Tree C > Tree A by Tukey test (Table 2). The average ED value in Tree B was significantly higher than that in Tree A. Moreover, the average LD and Dmin in Trees A and B were significantly higher than that in Tree C. The average Dmax in Tree B was significantly higher than that in Tree C. Thus, specimens of intermediate tree had larger RD than those of overtopped and dominant trees (intermediate > overtopped > dominant trees).

The differences in average RD, ED, LD, Dmin, and Dmax among the three radial positions were analyzed using ANOVA (Table 3). Significant differences in the RD components were observed between the three radial positions. A comparison of the average RD components of aged Japanese cedar trees is shown in Table 4. The average RD and LD in Rings A and B were significantly higher than that in Ring C by Tukey test. The average ED, Dmin, and Dmax values showed the following trend: Ring A > Ring B > Ring C. Thus, variations in average RD of the three zones showed the following trend: juvenile, transition > mature zones. Higher tree ring density is associated with juvenile wood close to the pith, whereas lower tree ring density is typical for mature wood toward the bark.

Inter-ring variation in ring density components of Japanese cedar trees is shown in Figure 2. Overall, the RD, ED, and Dmin in the radial direction slowly decreased from the pith outward to the bark side. The LD and Dmax in the radial direction increased from the pith outward to about the 10th ring number, constantly sustained to the 25th ring number, decreased to about the 35th ring number, and then increased to about the 50th ring number. Finally, it gradually increased toward the bark side. This trend is agreement with the result of above paragraph.

Overall, the specimens of Tree B, and Rings A and B had higher ring density than those of Trees C and A, and Ring C, respectively. Combining the above results shows that the average RD in the intermediate tree (Tree B) was significantly higher than in the dominant tree (Tree A) and the overtopped tree (Tree C); and the average RW in the intermediate tree (Tree B) was not significantly narrower than that in the dominant tree (Tree A) and the overtopped tree (Tree C). Furthermore, the juvenile wood (Ring A) not only had wider annual RW, but also had greater annual RD and variation. However, narrower annual RW, smaller annual RD, and less variation occurred in the mature wood (Rings B and C).

Latewood percentage

The difference in average LWP among three DBH groups was analyzed using ANOVA (Table 1). Significant difference in the LWP was observed between the three DBH groups. A comparison of the average LWP of aged Japanese cedar trees is shown in Table 2. The result

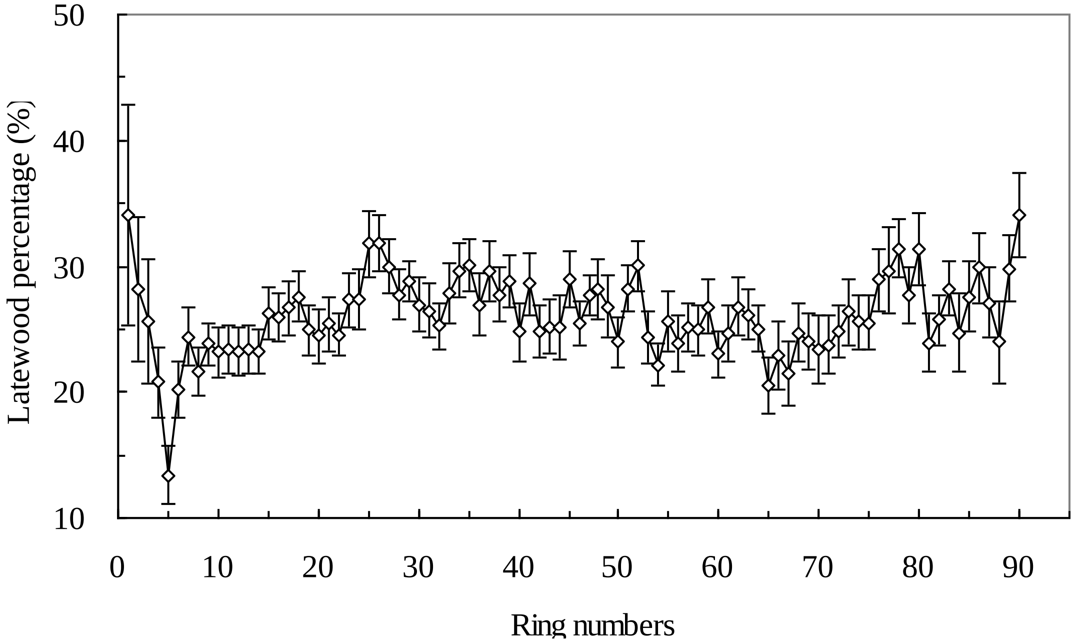

Figure 3. Inter-ring variation in average latewood percentage based on all rings at breast height of all sampled Taiwan yellow cypress trees.

showed that the average LWP values in Trees B and C were significantly higher than that in Tree A. Thus, specimens of intermediate and overtopped trees had larger LWP than that of dominant tree.

The difference in average LWP among the three radial positions was analyzed using ANOVA (Table 3). Significant difference in the LWP was observed between the three radial positions. A comparison of the average LWP of aged Japanese cedar trees is shown in Table 4. According to the result, the average LWP value showed the following trend: Ring B > Ring C > Ring A. Thus, variations in average LWP of the three zones showed the following trend: transition > mature > juvenile zones. Lower LWP is associated with juvenile wood close to the pith, whereas higher LWP is typical for transition and mature wood toward the bark.

Inter-ring variation in the LWP of Japanese cedar trees is shown in Figure 3. Overall, the LWP in the radial direction decreased from the pith outward to about the 5th ring number, increased to about the 26th ring number, and then decreased to about 65th ring number. Finally, it gradually increased toward the bark side. This trend is agreement with the result of above paragraph.

Overall, the specimens of Trees and Rings B and C had higher LWP than those of Trees and Rings A, respectively. The result displayed that the average LWPs in the overtopped tree (Tree C) and intermediate tree (Tree B) were significantly higher than that in the dominant tree (Tree A). Moreover, the average LWPs in the mature wood (Rings B and C) were significantly higher than that in the juvenile wood (Ring A).

Relationships between ring characteristics

Table 5 shows the correlation coefficients for all pair-wise comparisons of the ring characteristics based on all the rings of all sampled trees. Based on the results of this experiment, the EW and LW (wide components) were the most important factors determining the overall RW (coefficients of relationship (*r*) were 0.98 and 0.73, respectively ($p < 0.01$)). There were significant negative relations between the LWP and the RW ($r = -0.18$, $p < 0.01$), as well as the LWP and the EW ($r = -0.28$, $p < 0.01$). However, there was a positive relation between the LWP and the LW ($r = 0.28$, $p < 0.01$). The increments of growth (RW) were more concentrated in the EW than in the LW.

The ED, LD, Dmax, Dmin (density components), and LWP were the most important factors determining the overall RD. The coefficients of relationship (*r*) were 0.68, 0.51, 0.60, 0.53, and 0.64, respectively ($p < 0.01$). The tree RW (tree growth) did not correlate with tree RD ($r = 0.02$, $p > 0.05$). Moreover, the *r* values (< 0.42) were low, no matter what specimens came from different groups (the three Tree and Ring groups). This result indicated that tree growth rates of Japanese cedar tree are not likely to have a large impact on wood properties.

DISCUSSION

In this study, the average RW, RD, and LWP values of the aged trees based on all rings at the breast height of all

Table 5. Coefficients of relationships between the tree ring characteristics of Japanese cedar trees based on all rings at breast height of all sampled trees.

Variable	RW	EW	LW	RD	ED	LD	Dmin	Dmax	LWP
RW	1.00	0.98**	0.73**	0.02	0.16**	0.12**	0.05*	0.22**	-0.18**
EW		1.00	0.60**	-0.05*	0.13**	0.10**	0.02	0.17**	-0.28**
LW			1.00	0.30**	0.22**	0.19**	0.13**	0.33**	0.28**
RD				1.00	0.68**	0.51**	0.60**	0.53**	0.64**
ED					1.00	0.14**	0.85**	0.15**	0.21**
LD						1.00	0.07**	0.89**	0.11**
Dmin							1.00	0.10**	0.24**
Dmax								1.00	0.20**
LWP									1.00

Abbreviations are explained in the footnotes to Table 1. * Significant at the 5% level; ** significant at the 1% level by the *F*-test.

sampled trees were 2.46 mm, 400.6 kg m^{-3}, and 26.2%, respectively. For young Japanese cedar trees grown in Japan, Tsushima et al. (2006) reported that the wood basic density was 309-351 kg m^{-3}. Ishiguri et al. (2005) indicated that the annual ring width and average basic density were 2.24 to 3.06 mm and 312 to 330 kg m^{-3}, respectively. Zhu et al. (2005) indicated that the wood densities of 78-year-old plantation trees were 371 to 390 kg m^{-3}. For young Japanese cedar grown in Taiwan, Wang et al. (2008) reported that the ring widths, ring densities, and LWPs were 1.55 to 5.66 mm, 461.3 to 574.9 kg m^{-3}, and 24.6 to 35.2%, respectively. Lin et al. (2008) indicated that the average wood air-dried densities were 405 to 451 kg m^{-3}. Wang and Chen (1992) reported that the annual ring widths and LWPs were 1.26 to 7.57 mm and 15.8 to 22.8 %, respectively. Therefore, the results suggest that the ring width and wood density should be influenced by the various tree ages and varying environmental conditions of the silvicultural sites. Due to influences of different factors (genetic, climate, silvicultural practices, and other factors etc.), wood properties of Japanese cedar living tree should be investigated and understood.

In this experiment, the RW in the radial direction increased from the pith outward to about the fifth ring number, and then decreased at about the 20th to 30th ring number. Finally, it was almost constantly sustained or lightly decreased toward the bark side. Ishiguri et al. (2005) pointed out that the annual RW of the young Japanese cedar in their studies initially increased from the pith outward, and reached a maximum value at a certain age, then decreased rapidly towards the bark. Moreover, the age of reaching the maximum annual RW varied with the plantation spacing.

The largest overall cause of wood variation in conifers is the presence of juvenile wood and its relative proportion to mature wood. Nearly all wood properties, including both physical and chemical properties, greatly vary in the juvenile zone, but tend not to change much in the mature zone. There are different criteria to determine the juvenile period: for example, the ring width decreases from the pith outward for a number of years and then remains mostly constant in conifers (Zobel and Sprague, 1998; Haygreen and Bowyer, 1982). Csoka et al. (2005) reported that the position of demarcation between juvenile and mature wood of Japanese cedar trees occurs with about 17 to 22 and 10 to 25 ring numbers from the pith, respectively. In this experiment, transition between juvenile and mature wood as determined by visual interpretation of graphically plotted radial variation in ring width was at about the 20th to 30th ring numbers from the pith (juvenile-mature wood demarcation, Figure 1). In this study, the specimens of Tree A (dominant tree) and Ring A (juvenile wood) had wider ring width than those of Tree C (overtopped tree) and Rings B and C (mature wood, and Rings B > C), respectively.

In this study, the RD in the radial direction slowly decreased from the pith outward to the bark side. Ishiguri et al. (2005) pointed out that the annual basic density of young Japanese cedar in their study decreased from the pith towards the bark side. Panshin and de Zeeuw (1980) indicated that radial distribution patterns in wood density variations within cross-sections of mature tree trunks can be classified into three general types on the basis of the shapes of the curves for mean wood density from the pith outward to the bark. Type I increased from the pith to the bark, type II decreased outward from the pith, then increased to the bark, and type III decreased from the pith to the bark (ex. *Cryptomeria japonica*).

In this study, the average RD in the intermediate tree (Tree B) was significantly higher than in the dominant tree (Tree A) and the overtopped tree (Tree C); and the average RW in the intermediate tree (Tree B) was not significantly narrower than that in the dominant tree (Tree A) and the overtopped tree (Tree C). Furthermore, the juvenile wood (Ring A) not only had wider annual RW, but also had greater annual RD and variation. However, narrower annual RW, smaller annual RD, and less variation occurred in the mature wood (Rings B and C).

In this study, the specimens of Trees and Rings B and C had higher LWP than those of Trees and Rings A, respectively. The result displayed that the average LWPs in the overtopped tree (Tree C) and intermediate tree (Tree B) were significantly higher than that in the dominant tree (Tree A). Moreover, the average LWPs in the mature wood (Rings B and C) were significantly higher than that in the juvenile wood (Ring A). Wang and Chen (1992) reported that the LWP varies with tree age, and overall, increases with increases of the ring numbers from the pith. Saranpää (2003) pointed out that the LWP has been proven to be a good predictor of wood density in conifers, and the greatest variability of density occurs within each ring, due to seasonal climate changes and the formation of latewood.

In this study, the tree RW (tree growth) did not correlate with tree RD ($r = 0.02$, $p > 0.05$). Moreover, the r values (< 0.42) were low, no matter what specimens came from different groups (the three Tree, and Ring groups). This result indicated that tree growth rates of Japanese cedar tree are not likely to have a large impact on wood properties. Zobel and van Buijtenen (1989) and Saranpää (2003) assumed that there were positive and negative relationships, weak correlation, and no relationship between growth rate (or RW) and wood density. The wood density generally tended to decrease with increasing RW. However, the RD may significantly vary with various ring characteristics, as demonstrated in this study. Koga and Zhang (2002) indicated that the wood density of balsam fir (*Abies balsamea*) is significantly correlated with its components and LWP; and the wood density is not significantly correlated with RW. Taylor and Burton (1982) indicated that specific gravity was not significantly influenced by growth rate difference, and Kärenlampi and Riekkinen (2004) reported that the basic density is independent of growth rate, even if it is negatively correlated with ring width.

Dutilleul et al. (1998) reported that the relationship between RW and RD depends on the growth rate of Norway spruce (a negative relationship in slowly grown trees and no relationship in rapidly grown trees). Koga and Zhang (2004) reported that only a few of the correlations between ring width and wood density components of balsam fir (*Abies balsamea*) vary significantly with stem position from the stump to the stem top at the inter-tree level. Variations in ring width and ring density are complex and are affected by tree stem positions, cambium ages, growth traits, genetic factors, environmental conditions and other factors.

Conclusions

1. The RW parameters in the radial direction increased from the pith outward to the fifth ring number, and then decreased between about the 20th to 30th ring number (juvenile-mature wood demarcation). Finally, it was almost constantly sustained toward the bark side.
2. The RD in the radial direction slowly decreased from the pith outward to the bark side.
3. Wider tree rings and higher density are associated with Ring A (juvenile wood) close to the pith and narrower tree rings and lower density are typical for Ring B and C (mature wood) outward to the bark side.
4. The RD in the Tree B (intermediate tree) was higher than in the Tree A and C (dominant and overtopped trees); however, the RW in the intermediate tree was not narrower than in the dominant and overtopped trees.
5. The ED, LD, Dmax, Dmin (density components), and LWP were the most important factors determining the overall RD. The tree RW (tree growth) did not correlate with tree RD ($r = 0.02$, $p > 0.05$). This result indicated that tree growth rates of Japanese cedar tree are not likely to have a large impact on wood properties.

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