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ORIGINAL ARTICLE

# Effect of thinning on the ring characteristics of Japanese cedar plantation trees

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**Abstract** The purpose of this study was to explore the ring characteristics of Japanese cedar (*Cryptomeria japonica*) tree growth with thinning and unthinning regimes. The trees grown with thinning regimes increased in average ring width (RW), earlywood width, latewood width, ring density (RD), earlywood density, latewood density, maximum ring density, and latewood percentage (LWP) for the entire period of 16 years after thinning, as compared to those grown with unthinning regimes. The RW and RD components showed different reactions lasting several years after thinning. Overall, thinning caused immediate production (first year) of higher RD, lasting for several years; however, wider RW was delayed up to several years after treatment. There was a weak relationship between RW (growth rate) and wood density; and there were significant positive relationships between the RD and LWP. The results suggest that the compression wood produced after thinning.

**Keywords** Japanese cedar (*Cryptomeria japonica*) · Ring characteristics · Thinning

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## Introduction

Japanese cedar (*Cryptomeria japonica*) is a dominant species of plantations and is a potentially important timber resource in Taiwan. Tree growth can be directly managed by plantation techniques, including thinning treatment, which is an important practice for commercial plantation wood. It is generally recognized that wood properties and tree growth performance may be affected by thinning techniques. Zobel and van Buijtenen [1] assumed that there were positive, negative, weak relationships, and no effects between growth rate and wood density. One of those descriptions, increased growth rates result in growth rings with higher proportions of earlywood, is considered as a wood of lower density than latewood. In general, wood density should be negatively influenced by the tree growth rate in softwoods. During the investigation of some fundamental physical properties, an interesting phenomenon was observed when assessing the ring characteristics of Japanese cedar obtained from unthinning and thinning regimes. Both the ring width (RW) and ring density (RD) of trees seemed to increase after thinning compared to those of trees grown with an unthinning regime in the Chilan Mount. The phenomenon has never been found before in other sites of Taiwan. Furthermore, the RW and RD components showed different reactions several years after thinning.

Wang et al. [2] reported that the young Japanese cedar trees of more closely spaced plantations (3000 trees $ha^{-1}$) have higher wood density and compressive strength than those of more widely spaced plantations (2000 trees $ha^{-1}$); and different thinning treatments of the 2 initial spacings had little effect on ring characteristics and compressive strength. Wang and Chen [3], Wang and Lin [4], and Wang and Ko [5] reported that the narrower initial spacing of Japanese cedar trees produced larger values of wood density, bending strength, and modulus of elasticity compared to wider spacing (stand density, 400–10000 trees $ha^{-1}$). Ishiguri et al. [6] reported that initial spacing (1500–10000 trees $ha^{-1}$) of Japanese cedar did not affect basic density, the tracheid length of latewood or microfibril angle, and had a significant effect on annual ring width. Tsushima et al. [7] indicated that the wood properties of Japanese cedar were slightly influenced by initial spacing, although they were mainly influenced by inheritance factors. Aiura [8] reported that the diameter increment was significantly larger in the thinned plot than that in the unthinned plot at Harinoki. However, there was no significant difference (in diameter increment) at Totsumiya. Moreover, the difference between the thinned and unthinned plots increased after the third year.

It is well known that wood density and tree RW are affected by different types of thinning treatments; however, information on the effects of thinning on individual RD and RW is meager and fragmentary. Koga et al. [9] explored the annual radial growth rate in balsam fir (*Abies balsamea*) and found that the positive response to thinning lasted for 7 years, and the wood density tended to decrease following moderate thinning, due to a decreased latewood percentage (LWP). Peltola et al. [10] studied the effects of thinning on the diameter growth of Scots pine (*Pinus sylvestris* L.) by examining the response over the entire 12-year post-thinning period. Moreover, the effects of thinning treatment on wood properties encompass many factors and responses that increase, decrease, or have no effect on wood properties [1, 11].

Tree ring analysis is widely applied for many purposes. RW and RD parameters can be explored by X-ray densitometric techniques. Ring characteristics (RW and RD 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 [1, 12]. However, the influences of thinning treatments on the ring characteristics of Japanese cedar trees have yet to be the focus of in-depth investigation.

The present study explored and compared the individual ring characteristics of trees in a Japanese cedar plantation for several years after thinning and unthinning regimes using the X-ray densitometric technique.

## Materials and methods

The experimental trees are located in compartment 20, Taiping Mt. working cycle, Chilan Mt., Ilan County, northern Taiwan, as administered by the Veterans Affairs Commission, Executive Yuan, Taiwan. The mean annual temperature is 13.3°C, the RH is 90% (in the prevalent cloud zone), the mean annual precipitation is 3657 mm (2005–2006), and the elevation is 1100 m.

The area of this study site was about 2 ha. The Japanese cedar plantation stand was planted at a density of 3300 trees $ha^{-1}$ in 1966. It was divided into 16 smaller plots (12 thinned plots and 4 unthinned plots), each being 0.04 ha in area including the buffer zone. The two thinning treatments included thinning (basal area 22.5 $m^2$ $ha^{-1}$ at diameter at breast height, or DBH) and unthinning (44.1 $m^2$ $ha^{-1}$); these treatments were implemented in 1990 (24 years old). In the 12th year after thinning (36 years old), the basal area of the thinned area was 30.2 $m^2$ $ha^{-1}$ and that of the unthinned area was 52.2 $m^2$ $ha^{-1}$ (Table 1). Sampled trees ($n = 5$) with mean DBH classes were selected from each plot according to growth investigation, with a total of 80 sampled trees (60 and 20 trees from thinned and unthinned plots, respectively) being chosen to represent the thinned and unthinned stands.

An increment corer was used to cut cores 5 mm in diameter from samples trees. From the eastern aspect of each sample tree, we extracted a pith-to-bark increment core specimen at a position of DBH (same direction) in late 2006, when the specimens were 40 years old. All core specimens were mounted and processed into slices for X-ray densitometric scanning. However, a total of 30 sampled cores (25 and 5 cores from thinned and unthinned plots, respectively) were not ideal for further investigation. Therefore, a total of 50 core specimens (35 and 15 cores from thinned and unthinned plots, respectively) were further examined.

**Table 1** Structure of Japanese cedar stands grown with unthinning and thinning regimes

| Treatment | Age (year) | Mean DBH (cm) | Mean height (m) | Basal area ($m^2$ $ha^{-1}$) | Density (trees $ha^{-1}$) |
|---|---|---|---|---|---|
| No thinning | | | | | |
| | 24 | 19.6 | 15.6 | 44.1 | 1387 |
| | 36 | 23.2 | 18.5 | 52.2 | 1153 |
| Thinning | | | | | |
| Before thinning | 24 | 20.1 | 15.7 | 39.7 | 1250 |
| After thinning | 24 | 20.3 | 15.9 | 22.5 | 643 |
| After 13 years | 36 | 27.4 | 17.9 | 30.2 | 465 |

*DBH* diameter at breast height

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 (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 (25000 V). The standard collimator supplied with the QTRS-01X analyzer measures approximately 0.038 mm in width and 1.59 mm height at the detector. The sample step size can be adjusted at 0.02-mm increments. The determination of density by the QTRS-01X scanning system is based on the relationship between X-ray attenuation and density [13].

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 ($D_{max}$) and minimum density ($D_{min}$) 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 RW, earlywood width (EW), latewood width (LW), RD, earlywood density (ED), latewood density (LD), $D_{max}$, $D_{min}$, and LWP in rings across the sample. All specimens reached moisture contents (MC) 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.

## Results

### Ring width components

The average RW components based on the ≤24th ring numbers from pith of all sampled trees obtained from thinned plots (35 trees) were not significantly higher than those obtained from unthinned plots (15 trees) by *t* test (Table 2). Therefore, the average RW components of sampled trees before thinning obtained from thinned and unthinned plots were similar. The average RW, EW, and LW based on the 25th to 40th ring numbers from pith (16 years) of all sampled trees obtained from thinning plots were significantly higher than those obtained from unthinning plots by *t* test (Table 3). This indicates that thinning produces wider annual RW, EW, and LW than unthinning.

**Table 2** Average ring characteristics of all sampled trees before thinning (≤24 ring numbers from pith) obtained from unthinned (15 trees) and thinned plots (35 trees)

| Parameter | Unthinned | Thinned | Significant (*t* test) (*p*) |
|---|---|---|---|
| RW | 4.20 | 4.51 | 0.22 |
| EW | 3.19 | 3.47 | 0.20 |
| LW | 1.02 | 1.03 | 0.87 |
| RD | 493.8 | 508.2 | 0.32 |
| ED | 364.3 | 360.2 | 0.77 |
| LD | 830.9 | 863.5 | 0.27 |
| $D_{max}$ | 944.4 | 998.6 | 0.12 |
| $D_{min}$ | 256.2 | 229.8 | 0.02 |
| LWP | 26.3 | 28.1 | 0.36 |

*RW* ring width, *EW* earlywood width, *LW* latewood width, *RD* ring density, *ED* earlywood density, *LD* latewood density, $D_{max}$ maximum density in a ring, $D_{min}$ minimum density in a ring, *LWP* latewood percentage, *SD* standard deviation

**Table 3** Average ring characteristics based on the 25th to 40th ring numbers from pith of all sampled trees obtained from unthinned and thinned plots

| Parameter | Unthinned | Thinned | Significant (*t* test) |
|---|---|---|---|
| RW | 1.91 | 3.05 | $p < 0.001$ |
| EW | 1.35 | 2.11 | |
| LW | 0.56 | 0.94 | |
| RD | 491.1 | 538.1 | |
| ED | 333.0 | 353.3 | |
| LD | 868.1 | 898.5 | |
| $D_{max}$ | 978.4 | 1049.3 | |
| $D_{min}$ | 241.3 | 227.2 | |
| LWP | 29.0 | 32.4 | |

Abbreviations are explained in the footnotes to Table 2

Analysis of various ring number stages (25th to 40th ring number from pith) after thinning and a comparison of the average RW, EW, and LW of Japanese cedar trees treated with thinning and unthinning regimes (various 1st to 16th year(s) periods after thinning) are explored by *t* test. The result indicated that the thinning caused immediate production of higher LWs after the first year (1st to 1st to 16th). However, higher RWs occurred after the 3rd year by thinning (1st to 3rd to 1st to 16th, Fig. 1), and produced larger EWs after the 4th year (1st to 4th to 1st to 16th) by thinning. In this experiment, the effect of thinning on LW was clearly faster than the effects on RW and EW in the Japanese cedar plantation. Moreover, larger RW and EW were not induced in the first year after thinning, as compared to unthinning.

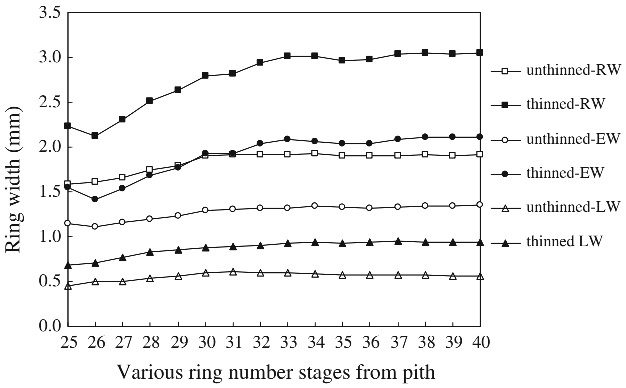


**Fig. 1** Radial variation in ring width based on various ring number stages (25th to 40th) from pith of all sampled Japanese cedar trees obtained from thinned and unthinned plots (I, standard error). The $p$ values of ring width based on various ring number stages from pith after thinning (25, 25–26, …, 25–39, and 25–40) (lasting year after thinning, 1st, 1st to 2nd, …, 1st to 15th, and 1st to 16th) were 0.25, 0.09, 0.02, 0.002, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, and <0.001, respectively ($t$ test)

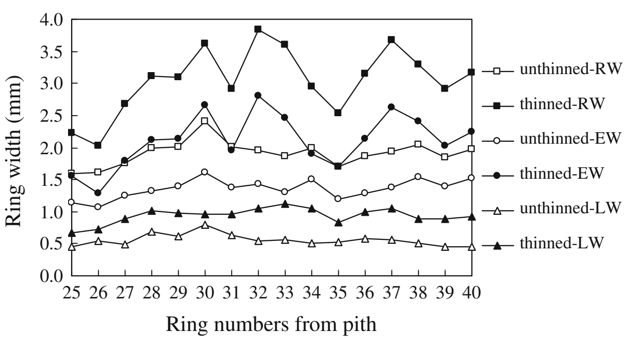


**Fig. 2** Radial variation in ring width based on the 25th to 40th ring numbers from pith of all sampled Japanese cedar trees obtained from thinned and unthinned plots (I, standard error). The $p$ values of ring width based on the 25th to 40th ring numbers from pith (25, 26, …, 39, and 40) (individual year after thinning, 1st, 2nd, … 15th, and 16th) were 0.25, 0.18, 0.18, 0.03, 0.04, 0.09, 0.01, 0.001, 0.001, 0.03, 0.04, 0.01, 0.004, 0.01, 0.01, and 0.01, respectively ($t$ test)

Analysis of individual ring number (each year) after thinning and a comparison of the average RW, EW, and LW of Japanese cedar trees treated with thinning and unthinning regimes are explored by $t$ test. The result indicated that the thinning caused immediate production of higher LWs in the first, 5th, and 7th to 16th years compared to unthinning, however, there were no significant differences in the other years after thinning. Larger RWs were found in the 4–5 and 7–16 years after thinning, however, there were no significant differences in the other years after thinning (Fig. 2). Wider EWs were shown in the 4, 7–9, and 12–16 years after thinning, however, there were no significant differences in the other years after thinning. These results reveal that the RW components had different reactions for lasting several years and individual year after thinning. Average ring characteristics based on different cumulated ring numbers and individual ring number from pith had to present reaction of lasting year and single year after thinning.

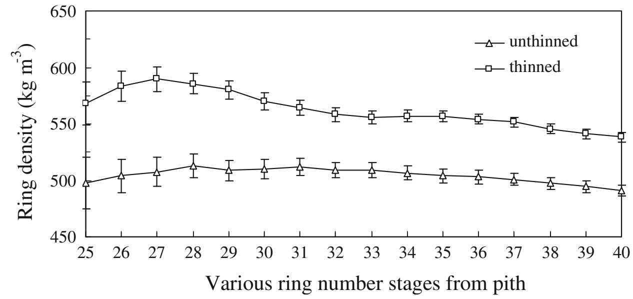


**Fig. 3** Radial variation in ring density based on various ring number stages (25th to 40th) from pith of all sampled Japanese cedar trees obtained from thinned and unthinned plots (I, standard error). The $p$ values of ring density based on various ring number stages from pith after thinning (25, 25–26, …, 25–39, and 25–40) (lasting year after thinning, 1st, 1st to 2nd, …, 1st to 15th, and 1st to 16th) were 0.04, 0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, <0.001, and <0.001, respectively ($t$ test)

## Ring density components

The average RD, ED, LD, and $D_{max}$ based on the ≤24th ring numbers from pith of all sampled trees obtained from thinned plots (35 trees) were not significantly higher than those obtained from unthinned plots (15 trees) by $t$ test (Table 2). Therefore, the average RD components (excepted $D_{min}$) of sampled trees before thinning obtained from thinned and unthinned plots were similar. The average RD, ED, LD, $D_{max}$ based on the 25th to 40th ring numbers from pith (16 years) of all sampled trees obtained from the thinning plots were significantly higher than those from unthinning plots by the $t$ test (Table 3). However, the average $D_{min}$ based on 25th to 40th ring numbers from pith of all sampled trees obtained from the thinning plots were significantly lower than those from the unthinning plots by $t$ test (Table 3). This indicates that thinning produces larger annual RD, ED, LD, and $D_{max}$ than unthinning; however, thinning induces smaller annual $D_{min}$ than unthinning.

Analysis of various ring number stages (25th to 40th ring number from pith) after thinning and a comparison of the average RD, ED, LD, $D_{max}$, and $D_{min}$ of Japanese cedar trees treated with thinning and unthinning regimes (various 1st to 16th year(s) periods after thinning) are explored by $t$ test. The result indicated that the thinning caused immediate production of higher RDs after the first year (1st to 1st to 16th, Fig. 3). However, higher $D_{max}$s occurred after the 2nd year by thinning (1st to 2nd to 1st to 16th), larger EDs produced after the 3rd year (1st to 3rd to 1st to 16th) by thinning, higher LDs were induced after the 14th year by thinning (1st to 14th to 1st to 16th), and lower $D_{\min}$s occurred after the 13th year (1st to 13th to 1st to 16th) by thinning. Our results indicated that the effect of thinning on RD was clearly faster than its effects on ED, LD, $D_{\max}$, and $D_{\min}$ in the Japanese cedar plantation.

Analysis of individual ring number (each year) after thinning and comparison of the average RD, ED, LD, $D_{\max}$, $D_{\min}$ of Japanese cedar trees treated with thinning and unthinning regimes are explored by *t* test. The result indicated that the thinning caused immediate production of higher RDs in the 1st to 3rd, 5th, and the 10th to 11th years when compared to the results of unthinning, however, there were no significant differences in the other years after thinning (Fig. 4). Larger $D_{\max}$s were found in 2–3 and 15–16 years after thinning, however, there were no significant differences in the other years after thinning. Larger ED was observed in the 4th year after thinning, however, there were no significant differences in the other years after thinning. Larger LD was shown in the 16th year after thinning, however, there were no significant differences in the other years after thinning. Lower $D_{\min}$s appeared in 7–8 and 14 years after thinning; however, there were no significant differences in the other years after thinning. These results displayed that the RD components had different reactions lasting several years and individual year after thinning.

## Latewood percentage

The average LWP based on the ≤24th ring numbers from pith of all sampled trees obtained from thinned plots (35 trees) were not significantly higher than those obtained from unthinned plots (15 trees) by *t* test (Table 2). The average LWP based on the 25th to 40th ring numbers from pith of all sampled trees obtained from the thinning plots was significantly higher than that from unthinning plots by *t* test (Table 3). This indicates that thinning produces larger annual LWP than unthinning.

Analysis of various ring number stages (25th to 40th ring number from pith) after thinning and comparison of the average LWP of Japanese cedar trees treated with thinning and unthinning regimes (various 1st to 16th year(s) periods after thinning) are shown in Fig. 5. According to the *t* test, the thinning caused higher LWPs after the 2nd year (1st to 2nd to 1st to 16th). This result showed that the effect of thinning on LWP was significant, as compared to that of unthinning.

Analysis of individual ring number (each year) after thinning and comparison of the average LWP of Japanese cedar trees treated with thinning and unthinning regimes are explored by *t* test. The result indicated that the thinning caused higher LWP in the 10th year (34-year-old tree) compared to unthinning, however, there were no significant differences in the other years after thinning.

## Relationships between ring characteristics

All pair-wise comparisons of the ring characteristics based on the 24th to 40th ring numbers from pith (for whole 16 years) of all sampled trees obtained from unthinned and thinned plots are explored by linear regression analysis, respectively. Based on the results of this experiment, the ED, LD, $D_{\max}$, $D_{\min}$, and LWP were the most important factors determining the overall RD, regardless of whether specimens came from the unthinned or thinned plots. The coefficients of relationship ($r$) were 0.57, 0.50, 0.48, 0.32, and 0.63 (unthinned); and 0.56, 0.40, 0.41, 0.52, and 0.62 (thinned), respectively ($p < 0.01$). The EW and LW were

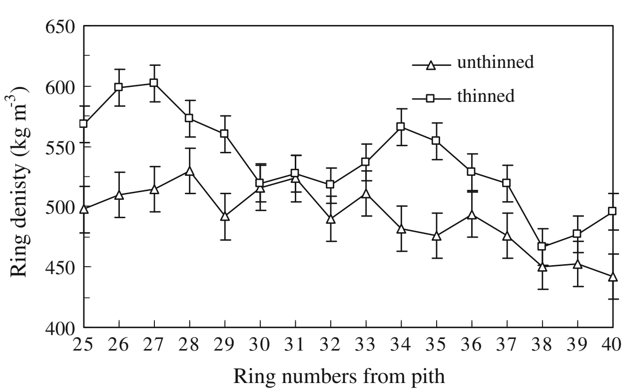


**Fig. 4** Radial variation in ring density based on the 25th to 40th ring numbers from pith of all sampled Japanese cedar trees obtained from thinned and unthinned plots (I, standard error). The *p* values of ring density based on the 25th to 40th ring numbers from pith (25, 26, …, 39, and 40) (individual year after thinning, 1st, 2nd, …, 15th, and 16th) were 0.03, 0.008, 0.008, 0.08, 0.02, 0.91, 0.87, 0.26, 0.24, 0.001, 0.01, 0.15, 0.08, 0.48, 0.32, and 0.06, respectively (*t* test)

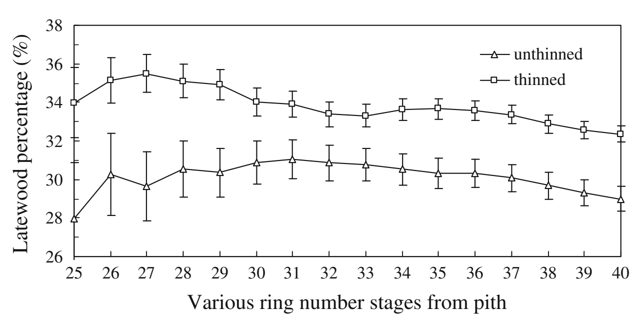


**Fig. 5** Radial variation in latewood percentage based on various ring number stages (25th to 40th) from pith of all sampled Japanese cedar trees obtained from thinned and unthinned plots (I, standard error). The *p* values of latewood percentage based on various ring number stages from pith after thinning (25, 25–26, …, 25–39, and 25–40) (lasting year after thinning, 1st, 1st to 2nd, …, 1st to 15th, and 1st to 16th) were 0.08, 0.03, 0.002, 0.005, 0.002, 0.02, 0.02, 0.03, 0.02, 0.002, <0.001, <0.001, <0.001, <0.001, <0.001, and <0.001, respectively (*t* test)

the most important factors determining the overall RW (unthinned, $r = 0.94$ and 0.71; and thinned, $r = 0.97$ and 0.71) ($p < 0.01$).

The tree RW was positively correlated with RD ($r = +0.13$, $p < 0.05$) based on the 25th to 40th ring numbers from pith of Japanese cedar obtained from unthinned plots and there was significant negative relationship between the tree RW and tree RD ($r = -0.20$, $p < 0.01$) of those specimens obtained from thinned plots. Moreover, there was significant negative relationship between the tree RW and RD ($r = -0.24$, $p < 0.001$) of those specimens obtained from thinned and unthinned plots, however, the $r$ values were small. Thus, these results indicated that there was a weak relationship between RW and wood density in Japanese cedar trees.

## Discussion

In this experiment, thinning produces wider annual RW, EW, and LW than unthinning. Wang and Chen [3] and Ishiguri et al. [6] reported that Japanese cedar trees grown with relatively wide spacing had wider annual ring widths. Some researchers have supported the finding that thinning treatments increase annual ring widths [9, 10, 14–17]. Aiura [8] showed that the effect of thinning on the diameter increment of Japanese cedar varied according to the tree growth performance (ex. diameter at breast height, tree height, height at the crown base, crown width, crown length etc.). Moreover, the effect of thinning at Harinoki was not evident in the first year after thinning in a plot at Harinoki, and the difference increased after the third year. Koga et al. [9] reported that the annual radial growth rate in balsam fir (*Abies balsamea*) showed a positive response to thinning lasting for 7 years and an only moderate thinning intensity is needed.

In this research, the average RD was 538.1 (thinned) and 491.1 (unthinned) kg m$^{-3}$ in Chilan Mount., north Taiwan. Lin et al. [18] reported that the average air-dried wood densities were 347–393, 390–483, and 484–518 kg m$^{-3}$ obtained from Xi-Tou, He-She, and Nei-Mao-Pu areas in middle Taiwan, respectively. Wang et al. [2] reported that the ring density (moisture content, 12%) of Japanese cedar was 463–486 kg m$^{-3}$ obtained from He–She area in middle Taiwan. Wang and Lin [4] reported that the air-dried wood density was 267–316 kg m$^{-3}$ obtained from Xi-Tou area. Ishiguri et al. [6] indicated that the basic wood density of Japanese cedar was 312-330 kg m$^{-3}$ obtained from Funyu, Japan. Moreover, Lin et al. [18] indicated that wood density of Japanese cedar plantation was affected by different silvicultural sites.

In this study, the thinning (based on the 25th to 40th ring numbers from pith) not only produced wider RW components but also caused larger annual RD, ED, LD, and $D_{max}$ than those specimens of trees obtained from unthinned plots. Previous studies have reported some results on the effects of thinning on wood density. Zobel and van Buijtenen [1], Koga et al. [15], Mörling [16], and Guller [17] stated that thinning has little or no effect on wood density. Jaakkola et al. [19] concluded that thinning resulted in increased growth in both earlywood and latewood; and the EW increased somewhat more than the LW, thus causing a slight reduction in wood density. However, the thinning of Norway spruce trees (*Picea abies*) did not result in significant reduction of wood density. Barbour et al. [14], Koga et al. [9], and Jones and Fox [20] suggested that wood density is reduced by thinning treatments. Moreover, some reports have shown that thinning treatments cause an increase in wood density [21, 22]. Zobel and van Buijtenen [1] reviewed some reports for some species. For example, they stated that the wood density of *Picea abies* tree is greater after heavy thinning and is remarkably affected in good sites; thinned 50-year-old *Larix occidentalis* trees increased in wood density for 15 years after thinning; and wood density and latewood content increased for 4 years after thinning in a 9-year-old *Pinus taeda* stand. From Wang et al. [2], Wang and Chen [3], Wang and Lin [4], Ishiguri et al. [6], and Tsushima et al. [7] reported that the Japanese cedar trees grown at relatively wide spacing had or not wider ring width than those grown at relatively narrow spacing; and, trees grown at relatively wide spacing had or not lower wood density than those grown at relatively narrow spacing.

In this study, the wide RW contain a high proportion of latewood in Japanese cedar trees obtained from thinned plots, and the contrast between earlywood and latewood is often less distinct than in trees obtained from unthinned plots (Fig. 6). Moreover, tree ring in cross section was

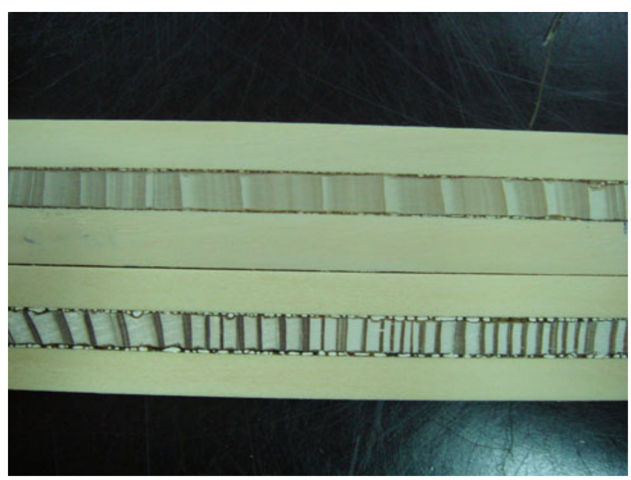

**Fig. 6** Tree ring in cross section of X-ray specimen obtained from thinned plots (up, no. 8–69) and unthinned plots (down, no. 0–85)

observed at X-ray specimen by stereomicroscopy. Tracheid cells were partly and approximately rounded rather than rectangular and have pronounced intercellular spaces between cells. Therefore, the compression wood (wider RW and higher RD) may be caused by wind function after thinning. Haygreen and Bowyer [23] reviewed that thinning has been found to have an effect upon the development of compression wood; thinning in the same location, uneven thinning, or thinning on a steep slope can cause uneven crown development, a tendency for crooked boles, and even compression wood development. Panshin and de Zeeuw [24] indicated that the general appearance of compression wood is usually indicated by eccentric growth rings which appear to contain an abnormally large proportion of latewood in the region of fastest growth, and the presence of compression wood in softwood causes the transition from early to latewood to become quite gradual on the cross section. Moreover, the most evident physical characteristic of compression wood is the increase in wood density over that shown by comparable normal wood.

Mattheck and Breloer [25] indicated that the most important and most dangerous load on the tree is undoubtedly that created by wind, which can introduce bending stresses near the periphery of the stem. Wang and Chiu [26] reported that wind-broken portions always occur at the lower 1/5–2/5 (at about 1.3 m above the ground) of total tree height in Japanese cedar. In this experiment, all increment core specimens were sampled from at breast height. We observed in the field (site) that wind break had occurred and the mortality was average 16.9% (unthinned) and 21.1–35.1% (thinned) for 16 years after thinning. The phenomena of wind action might have affected the growth ring of remaining Japanese cedar trees after thinning; and the stress of tree should be produced and reacted on the trunk near the breast height. The values of RW and wood density might increase with increased wind load. Therefore, the wind action and compression wood may cause wider RW and higher RD of Japanese cedar in this experimental region.

In this study, thinning produced larger annual LWP than unthinning (Table 3; Fig. 5). Furthermore, there were significant positive relationships between the tree RD and LWP obtained (thinned and unthinned). Guller [17] reported that the lowest mean LWP occurs with heavy thinning treatment and that the LWP of moderate thinning treatment is higher than other treatments in *Pinus brutia*. Zobel and van Buijtenen [1] indicated in a review that thinning allowed latewood growth to increase, producing an overall increase in wood density. Hence, thinning stimulates latewood production, leading to increased wood density.

According to the above results of the analysis of various ring number stages after thinning, the thinning caused immediate production of higher RD after the first year; and produced larger RW after the 3rd year (1st to 3rd to 1st to 16th) by thinning. According to the analysis of individual ring number after thinning, the thinning caused higher RD in the 1st to 3rd or 5th year (25 years old, lasting 3–5 years) and in the 10th to 11th years (34 years old, lasting 2 years) after treatment, however, thinning treatment formed larger RW after the 4th year (4th to 16th, except 6th year). Thinning caused immediate production (first year) of higher RD lasting several years; however, wider RW was delayed for up to several years after treatment. Observation in the field showed that light natural thinning (wind action) occurred after artificial thinning (24 years old) in this experimental plantation stand. The wind break had occurred and the mortality was average 16.9% (unthinned) and 21.1–35.1% (thinned) for 16 years after thinning. From the above reaction of ring characteristics, the light natural thinning was evaluated and occurred in trees that were about 34 years old (Figs. 3, 4, 5, reactions of RD and LWP).

In this study, thinning treatment generally enhance the tree growth. Actually, the results obtained here showed that RW and RD significantly increased after thinning treatment. Moreover, there was a weak relationship between RW and wood density in Japanese cedar trees. A form of different intensity of the compression wood was associated with accelerated growth after thinning and different wind actions and functions. Zobel and van Buijtenen [1] reviewed that growth rate is only one of many factors that can influence wood density.

Zhang [27], Kennedy [28], and Koga and Zhang [29] reported that wood density generally tends to decrease with increasing RW. Koga et al. [9] indicated that the wood density of balsam fir (*Abies balsamea*) is significantly correlated with its components and LWP; and wood density is not significantly correlated with RW. Taylor and Burton [30] indicated that wood density is not significantly influenced by growth rate, and Kärenlampi and Riekkinen [31] reported that the basic density is independent of growth rate, even if it is negatively correlated with RW. Dutilleul et al. [32] reported that the relationship between RW and RD depends on the growth rate of Norway spruce (with a negative relationship in slowly grown trees and no relationship in rapidly grown trees).

Tong et al. [33] indicated that with increasing DBH, wood density and modulus of rupture are decreased by thinning, however, a moderate thinning intensity had much less effect on wood properties; and it is possible to produce high-quality lumber from dense black spruce (*Picea mariana*) plantations with appropriate thinning treatments. Our results indicate that there was significant weak relationship between the RW and RD throughout the entire period of 16 years after thinning and unthinning treatments. Moreover, the thinning caused wider RW and larger RD than unthinning, and the compression wood produced after thinning.

## Conclusions

1. The trees grown with thinning increased in average RW, EW, LW, RD, ED, LD, $D_{max}$, and LWP for the entire period of 16 years after thinning compared to those grown with unthinning.
2. According to analysis of various ring number stages after thinning, the thinning caused immediate production of higher RD and LW after the first year. However, higher $D_{max}$ and LWP occurred after the 2nd year (1st to 2nd to 1st to 16th) by thinning, and larger RW and ED were produced after the 3rd year (1st to 3rd to 1st to 16th) by thinning.
3. Analysis of individual ring number after thinning showed that the thinning caused higher RD lasting 3–5 years (1st to 3rd or 5th) after treatment, however, larger RW was formed after the 4th year (4th to 16th, except 6th) by the treatment.
4. There was a weak relationship between RW (growth rate) and wood density in Japanese cedar trees.
5. The RW and RD components had different reactions for lasting several years after thinning. The results suggest that the compression wood produced after thinning.

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