J Wood Sci (2011) 57:352–362
DOI 10.1007/s10086-011-1184-z

ORIGINAL ARTICLE

Cheng-Jung Lin · Chih-Hsin Chung · Shu-Tzong Lin

Ring characteristics and screw withdrawal resistance of naturally regenerated *Chamaecyparis obtusa* var. *formosana* trees

Received: May 6, 2010 / Accepted: February 21, 2011 / Published online: June 24, 2011

Abstract The ring characteristics and screw withdrawal resistance (SWR) of naturally regenerated Taiwan yellow cypress (*Chamaecyparis obtusa* var. *formosana*) trees were explored. Significant differences in average ring width (RW), earlywood width, latewood width, ring density (RD), earlywood density (ED), latewood density (LD), highest density (D_{max}), lowest density (D_{min}), latewood percentage (LWP), and SWR were observed between trees, rings (SWR excluded), and tree height positions. The RW components in the radial direction increased from the pith outward to about the 3rd to 5th ring and then decreased to about the 25th ring; 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. Average ring width and ring density were significantly affected by the various tree growth rates, radial ring numbers, and tree height positions. ED, LD, D_{max}, D_{min}, and LWP were the most important factors determining the overall RD. RW did not correlate with tree RD. SWR is correlated with ED, RD, D_{min}, LWP, and intra-ring density variation (IDV). Thus, the SWR can be used to predict wood density and in nondestructive evaluation of a living tree.

Key words Taiwan yellow cypress (*Chamaecyparis obtusa* var. *formosana*) · Naturally regenerated tree · Ring characteristics · Screw withdrawal resistance

Introduction

Naturally regenerated Taiwan yellow cypress (*Chamaecyparis obtusa* var. *formosana*) is a dominant ecological species and an important timber resource at Chi-Lan Mt., northern Taiwan. Conservation ethics and wood resource shortages have stimulated sustainable forest management to meet the social, ecological, economic, cultural, and spiritual needs of present and future generations. Naturally regenerating Taiwan yellow cypress stands should be managed to maintain forest health, ecological diversity, and the adequate provision of wood resources. People concerned with forest conservation and wood utilization would benefit from knowing tree growth performance (e.g., ring width) and wood quality traits (e.g., ring density). Some studies[1–3] have reported the growth performance or wood properties of naturally regenerated Taiwan yellow cypress trees. Chiu et al.[1] reported high correlation among diameter at breast height (DBH), tree height, and crown growth parameters of Taiwan yellow cypress trees. Yang[2] investigated variation of crown morphology and structure pattern of different crown class Taiwan yellow cypress trees to elucidate growth adaptation. Lin et al.[3] examined tree growth performance, ring characteristics, and compressive strength of Taiwan yellow cypress trees. However, there has been little investigation concerning corresponding wood properties and details of variation of naturally regenerated Taiwan yellow cypress trees. This study was one of a series of investigations on tree growth performance and wood properties of these cypress trees to elucidate their tree growth variation and wood diversity from the aspect of forest ecological management.

Tree ring analysis is widely applied for many purposes (e.g., dendroarcheology, dendrochronology, and dendroclimatology). The ring width and density parameters can be explored by X-ray densitometric techniques. Ring characteristics (e.g., ring width, ring density, and latewood percentage) 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.[4,5]

C.-J. Lin (✉)
Department of Forest Utilization, Taiwan Forestry Research Institute, 53 Nanhai Rd., Taipei 100, Taiwan
Tel. +886-2-23039978; Fax +886-2-23035738
e-mail: d88625002@yahoo.com.tw

C.-H. Chung
Department of Forest Management, Taiwan Forestry Research Institute, Taipei 100, Taiwan

S.-T. Lin
Department of Natural Resources, National Ilan University, Ilan 260, Taiwan

Large tree-to-tree (inter-tree) and within-tree (intra-tree) (radial, axial, and inter-ring/within-ring) variations in wood properties are observed in a species, even if the trees are of the same age and have been grown under the same conditions.[5,6] Panshin and de Zeeuw[7] suggested that understanding the extent of variability of wood is important because the uses for each kind of wood are related to certain of its characteristics. The properties of wood are influenced by such parameters as tree cambium age, genetic factors, and environmental state.

Intra-ring density variation (IDV) was adopted using a model for expressing the pattern curve from earlywood to latewood as a power function.[8–11] We wished to understand the change amplitude of wood density from earlywood to latewood (intra-ring) of yellow cypress trees. Lin et al.[3] reported significant relationships between tree growth performances; tree ring density and compressive strength were not correlated with tree DBH growth rate. Moreover, significant differences in average ring width were observed between trees and between rings; also, although average ring density was observed between trees, no difference was observed between rings. Moreover, no details of ring variation were reported. We were therefore interested in variations of ring characteristics in the radial (from the pith to the bark) and vertical (from the base to the top of the tree) directions in the trunks of naturally regenerated trees.

During the past 20 years, forest scientists have developed and used nondestructive evaluation (NDE) techniques for a wide range of applications from grading lumber to evaluating living trees. The dynamic modulus of elasticity (MOE, density × square of the wave velocity) is one of most commonly used NDE criteria for estimating wood properties.[12] However, measuring the wood density of a standing tree is more difficult than measurements under solid wood material conditions. Screw withdrawal resistance (SWR) is one of the NDE techniques that can be used to estimate wood density and wood properties. The Forest Products Laboratory[13] and Cai et al.[14] indicated good correlation between screw withdrawal strength and the density of solid wood; the predicted density of in situ wood members with stress wave propagation produced good correlation with the static MOE. Several studies indicated that the physical properties of wood-based materials (fiberboard, particleboard, plywood, etc.) are statistically correlated to screw withdrawal strength.[15–19] Currently, there is concern about using the SWR technique to evaluate the wood properties of standing tree with a portable withdrawal meter.

Therefore, the purposes of this study were to explore variations of ring characteristics and withdrawal resistance of naturally regenerated Taiwan yellow cypress trees in different trees, rings, and tree height positions.

Materials and methods

The experimental trees are located in compartments 31 and 32, 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, RH is 90%, mean annual precipitation is 3,657 mm (2005–2006), and elevation is 1,700 m.

The naturally regenerated Taiwan yellow cypress stand was implemented by natural seed tree regeneration method (one of natural regenerations) in about 1961; subsequently, this stand has had no silvicultural treatment. Tree growth performance was investigated[2] in 2006: average forest stand density is 3,052 ± 573 trees ha^{-1}, and diameter at breast height (DBH), tree height (TH), height at crown base (HCB), crown width (CW), crown length (CL = TH − HCB), crown ratio (CR = CL/TH), and crown thickness index (CTI = CW/CL)[20] were 4.5–22.6 cm, 5.3–12.9 m, 3.5–5.8 m, 1.1–2.3 m, 1.8–7.1 m, 0.33–0.55, and 0.33–0.67, respectively. These tree growth performance data are an important foundation for deciding which trees to sample and understanding the corresponding wood properties.

Four plots (0.05 ha/plot) were established in the naturally regenerated stand. Sampled trees ($n = 4$) of different diameter classes (normal distribution) were selected from each plot according to the growth investigation of Yang.[2] A total of 16 sample trees was cut down, representing the naturally regenerated stand. These trees were harvested in late 2006, when the trees were about 13–40 years old (age determined at 0.3 m above the ground by a tree ring analysis, uneven-aged stand).

Cross-sectional disks (10 cm thick) were cut from each sample tree at the positions of 0.3, 1.3, 3.3, 5.3, 7.3, and 9.3 m above ground. A diametrical strip about 20 mm wide (passing through the pith) was sawn from each disk in the same direction. A thin slice (2 × 20 mm, longitudinal × tangential) for X-ray scanning was cut from each strip, and the remainder of the strip was used for withdrawal resistance detection. The strips were conditioned at a moisture content (MC) of 12%. The SWR of the strips was then determined by the withdrawal resistance method at the bark side (in the radial direction, from the bark to the pith).

The dimensions of the wood screw used in this experiment were total length, 40 mm; length of threaded portion, 15 mm; shank diameter, 3.8 mm; diameter of threaded portion, 4.8 mm. A screw was inserted at the bark side (radial direction, bark peeled off) of a disk sample to a 15-mm depth (fixed screw position) by a screwdriver. Then, the maximum withdrawal resistance of each screw (by pulling the screw out of the wood sample) was obtained using a potable withdrawal force meter (Hong-Da, Taipei, Taiwan) under a constant loading rate. A potable withdrawal force meter was connected to the digitized monitor, and the SWR value was displayed on the meter screen and recorded. Before the formal experiment, a preliminary test of 150 small clear specimens [32 (longitudinal) × 20 (tangential) × 20 mm (radial)] was conducted by screw withdrawal and static bending tests to ascertain feasibility. Significant positive relationships were found for SWR with wood density and for wood density with modulus of rupture.

An X-ray densitometric technique determined the ring characteristics of the slices. 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 [QTRS-01X Tree Ring

Analyzer; Quintek Measurement Systems (QMS), Knoxville, TN, USA] for ring characteristics. Each slice (at 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 wide and 1.59 mm high 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 of X-ray attenuation and density.[21]

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 Tree Ring Analyzer was calibrated to the actual sample density (from strips); the density profile can then be measured and produced. The earlywood/latewood boundary was determined by a comparator, and the location was then converted into a density threshold in the density profile. A ring density boundary was identified by a fixing 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 a ring. Therefore, density profile and ring characteristics could be confirmed and determined with a tree-ring analysis program (attached to the QMS). The ring characteristics included average tree ring width (RW), earlywood width (EW), latewood width (LW), tree ring density (RD), earlywood density (ED), latewood density (LD), D_{max}, D_{min}, latewood percentage (LWP), and IDV (D_{max}-RD)/(RD-D_{min}) in a ring across the sample.

Results and discussion

Ring characteristics and screw withdrawal force

Table 1 summarizes the average ring characteristics based on all rings at all heights of all sampled naturally regenerated Taiwan yellow cypress trees. The average RW value (2.01 mm) and the average RD value (473.4 kg m^{-3}) of the naturally regenerated trees are similar to those mentioned (ring width and basic density, 2–3 mm and 380–440 kg m^{-3}, respectively) by Guo[22] and the ring density (452.6 kg m^{-3}) reported by Lin et al.[3] However, the latewood percentage (30.4%) was larger than that reported (16.4–25.0%) by Guo[22] and is similar to the result (30.9%) of Lin et al.[3] The average screw withdrawal resistance based on all heights of all sampled trees was 147.0 kg. Cai et al.[14] reported the specific gravity and withdrawal load of southern pine specimens are about 0.40–0.80 and 113–227 kg, respectively.

Table 1. Average of ring characteristics and screw withdrawal resistance (SWR) of naturally regenerated Taiwan yellow cypress trees based on all rings (excluded SWR) at all heights of all sampled trees (*n* = 16)

Characteristics	Mean value	SD
Width (mm)		
Ring	2.01	0.66
Earlywood	1.40	0.49
Latewood	0.61	0.17
Density (kg m^{-3})		
Ring	473.4	43.3
Earlywood	410.4	32.4
Latewood	571.2	44.4
Highest	692.1	49.1
Lowest	368.7	32.9
LWP (%)	30.4	3.5
IDV	2.20	0.39
SWR (kg)	147.0	22.6

LWP, latewood percentage; IDV, intra-ring density variation; SD, standard deviation

Ring width

Differences in average ring width, earlywood width, and latewood width among sampled trees, tree rings, and tree height position were assessed with analysis of variance (ANOVA) (Table 2). Significant differences in the RW components were observed between trees, rings, and tree height positions.

Variation in ring width components (RW, EW, and LW) among Taiwan yellow cypress trees (nos. 1–16) is presented in Fig. 1. Inter-ring variation in ring width components of Taiwan yellow cypress trees is shown in Fig. 2. The RW parameters in the radial direction increased from the pith outward to about the 3rd to 5th rings and then decreased to about the 25th ring. Finally, the parameter was almost constantly sustained toward the bark side. Lin et al.[3] reported that the position of demarcation between juvenile and mature wood occurred at about 25–30 years of cambium age by RW, compressive strength variation, and segmented regression analyses.

Because only one sampled tree was more than 11.3 m in height, those measurements and analysis were excluded here. Inter-tree height position variation in ring width components of Taiwan yellow cypress is presented in Fig. 3. Average ring width and earlywood width slowly increased with tree height from 0.3 m to 9.3 m. Average RW values showed a trend as follows: 9.3 m > 5.3 m, 3.3 m, 1.3 m, and 0.3 m; 7.3 m > 3.3 m, 1.3 m, and 0.3 m; 5.3 m > 3.3 m and 0.3 m, by Tukey test. Average RW values tended to increase with increasing tree height.

In this experiment, all 16 sampled trees can be classified into two groups based on average ring width of the individual tree, namely, growth A (fast growth group: RW 2.11–3.27 mm, 8 trees) and growth B (slow growth group: RW 0.96–1.89 mm, 8 trees). Average ring width in growth A group was significantly greater than that in growth B group by *t* test (2.57 vs. 1.54 mm, $P < 0.05$). All ring numbers were separated into two groups by radial position: ring A (from the 1st outward to the 20th ring) and ring B (from 21st ring outward to the bark side). Average ring width of ring A group was significantly greater than that of ring B group by *t* test (2.77 vs. 1.77 mm, $P < 0.05$). All measurements of

Table 2. Results of analysis of variance (ANOVA) for differences in the ring characteristics of Taiwan yellow cypress among trees, rings, and tree height positions

Variance	Tree	Ring	Tree height	Residual	Total
Degrees of freedom	15	39	5	1,712	1,772
Width					
Ring					
Sum of squares	808.7	1,233.7	134.3	1,055.4	11,902.2
Mean square	53.9	31.6	26.9	0.62	
F value	87.5**	51.3**	43.6**		
Earlywood					
Sum of squares	278.6	196.4	30.0	704.7	4,318.1
Mean square	18.6	5.0	6.0	0.41	
F value	45.1**	12.2**	14.6**		
Latewood					
Sum of squares	150.9	512.1	43.7	677.7	2,778.0
Mean square	10.1	13.1	8.7	0.40	
F value	25.4**	33.2**	22.1**		
Density					
Ring					
Sum of squares	1,923,936	564,028	226,160	2,524,659	3.8E + 08
Mean square	128,262.4	14,462.3	45,231.9	1,474.7	
F value	87.0**	9.8**	30.7**		
Earlywood					
Sum of squares	1,238,533	456,289	258,504	1,345,883	2.87E + 08
Mean square	82,569	11,700	51,701	786.1	
F value	105.0**	14.9**	65.8**		
Latewood					
Sum of squares	2,518,807	156,021	156,792	2,887,359	5.61E + 08
Mean square	167,920	4,001	31,358	1,687	
F value	99.6**	2.37**	18.6**		
Highest					
Sum of squares	3,897,169	1,123,827	396,427	11,945,475	8.55E + 08
Mean square	259,811	28,816.1	79,285	6,977.5	
F value	37.2**	4.1**	11.4**		
Lowest					
Sum of squares	1,102,436	599,228	168,800	1,865,149	2.3E + 08
Mean square	73,496	15,365	33,760	1,089	
F value	67.5**	14.1**	31.0**		
LWP					
Sum of squares	16,095	95,891	12,314	404,640	3,161,090
Mean square	1,073	2,459	2,463	236	
F value	4.5**	10.4**	10.4**		
IDV					
Sum of squares	174.2	41.1	19.9	1,326	11,181
Mean square	11.6	1.05	3.99	0.77	
F value	15.0**	1.36	5.15**		

LWP, latewood percentage; IDV, intra-ring density variation

*Significant at 5% level by *F* test

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

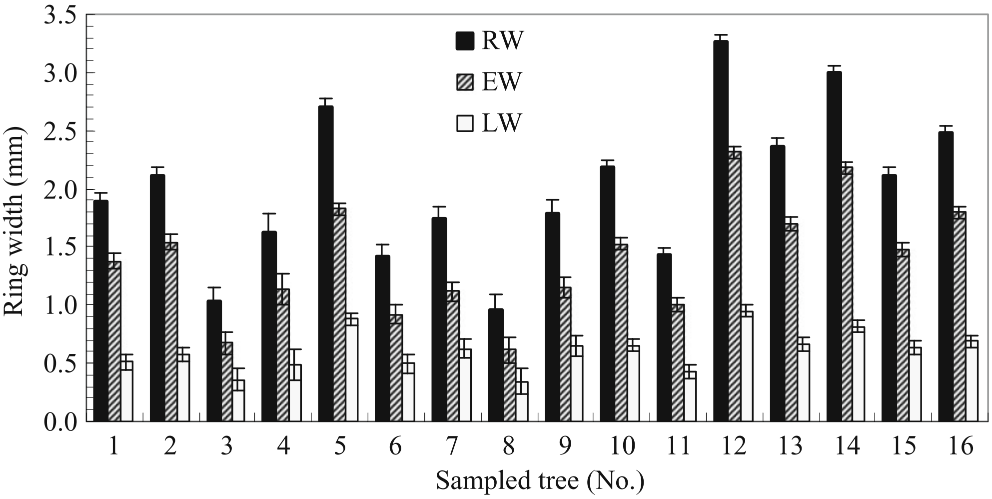


Fig. 1. Inter-tree variation in ring width (*RW*) components based on all rings at all tree heights of naturally regenerated Taiwan yellow cypress trees. *I*, standard error; *EW*, earlywood; *LW*, latewood

Fig. 2. Inter-ring variation in ring width (*RW*) components based on all rings at all heights of all sampled Taiwan yellow cypress trees. *EW*, earlywood; *LW*, latewood

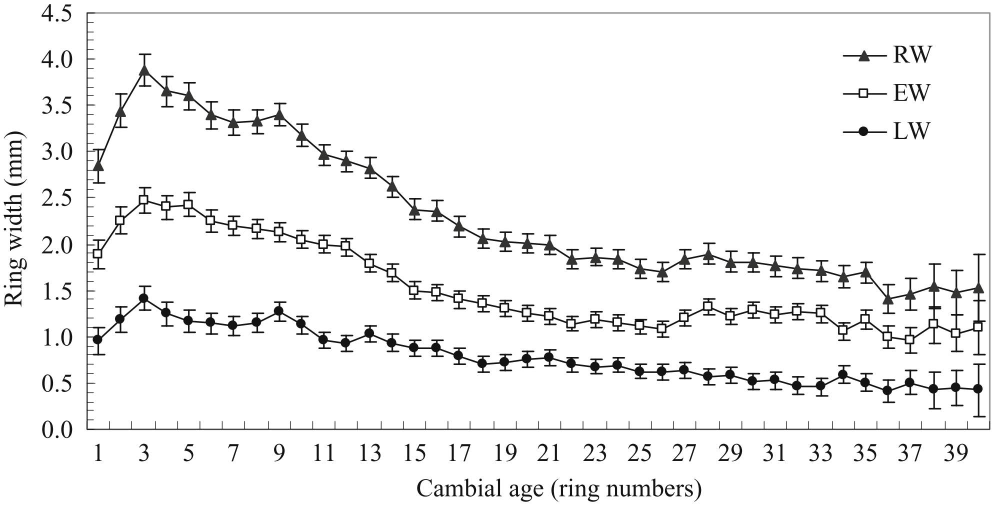
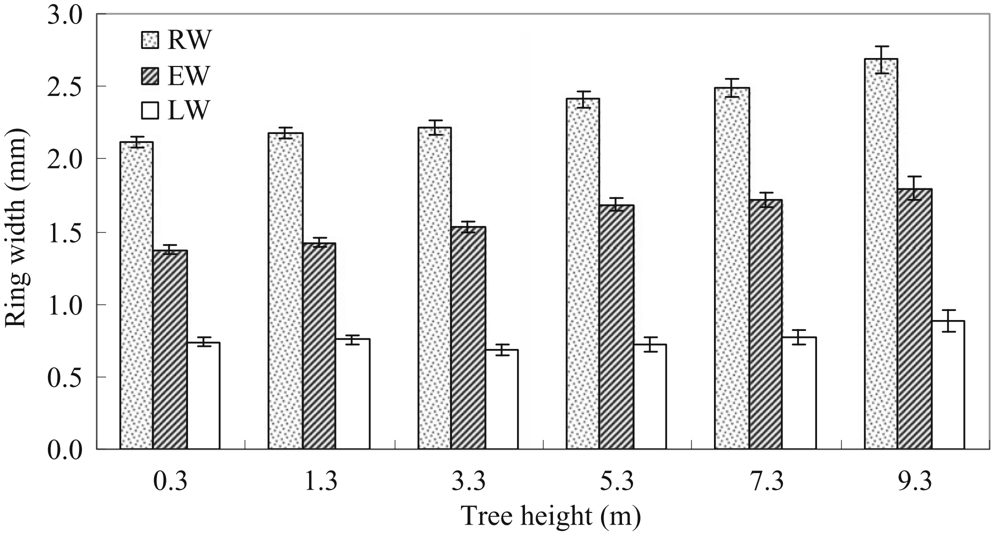


Fig. 3. Inter-tree height positions variation in ring width (*RW*) components based on all rings at all heights of all sampled Taiwan yellow cypress trees. *EW*, earlywood; *LW*, latewood



various tree heights at the positions of 0.3, 1.3, 3.3, 5.3, 7.3, and 9.3 m above ground were sorted into two groups: height A (0.3–3.3 m) and height B (5.3–9.3 m). Average ring width of height B group was significantly greater than that of height A group by *t* test (2.48 vs. 2.16 mm, $P < 0.05$). Therefore, the specimens classified as growth A, ring A, and height B had greater ring width than those of growth B, ring B, and height A, respectively.

Significant difference in average ring width was observed between tree growth groups by radial position interaction (growth × ring) by one-way ANOVA ($P < 0.01$). Average ring width in the four groups showed the following trend: growth A × ring A (3.44 mm) > growth A × ring B (1.96 mm) and growth B × ring A (1.81 mm) > growth B × ring B (1.09 mm) by Tukey test.

A significant difference in average ring width was observed between radial by tree height position interaction (ring × height) by ANOVA ($P < 0.01$). Average ring width in the four groups showed the following trend: ring A × height B (3.24 mm) > ring A × height A (2.70 mm) > ring B × height B (2.25 mm) > ring B × height A (1.43 mm) by Tukey test.

Moreover, a significant difference in average ring width was observed between tree growth by tree height position interaction (growth × height) by ANOVA ($P < 0.01$). Average ring width in the four groups showed the following trend: growth A × height B (2.59 mm) and growth A × height A (2.56 mm) > growth B × height B (1.70 mm) > growth B × height A (1.53 mm) by Tukey test.

A significant difference in average ring width was observed between tree growth by radial by tree height position interaction (growth × ring × height) by ANOVA ($P < 0.01$). The difference in average ring width for various groups was analyzed using the Tukey test (Table 3). The mean ring widths of the growth A × ring A × height A/height B group were the greatest and those of the growth B × ring B × height A group were the smallest among the eight groups.

In the present work, specimens were collected from naturally regenerated trees, which may explain the large variations in ring width components, and tree growth diversity was seen in the uneven-aged stand (different tree sizes, inter-tree). Experienced observations in the field noted that naturally regenerated Taiwan yellow cypress trees have slower growth than that of plantation trees grown in even-aged stands. Hence, the RW components may be affected by environment conditions such as tree competition, plantation spacing, and stand density.

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, both physical and chemical, 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, ring width decreasing from the pith outward for a number of years and then remaining mostly constant in conifers.[6,23] Therefore, the RW components may be affected by cambial age (ring number).

Ring density

Differences in average ring density, earlywood density, latewood density, highest density, and lowest density in a ring among sampled trees, rings, and tree height position were analyzed using ANOVA (see Table 2). Significant differences in the RD components were observed between trees, rings, and tree height positions.

Table 3. Comparison of the average ring width and ring density according to interaction among two tree growth classes and two radial ring positions and two tree height positions

Variables	RW	RD
Growth A × ring A × height A	3.46^{a}	$457.8^{c,d}$
Growth A × ring A × height B	3.35^{a}	$470.2^{c,d}$
Growth A × ring B × height A	1.62^{d}	427.8^{e}
Growth A × ring B × height B	2.35^{b}	$444.7^{d,e}$
Growth B × ring A × height A	$1.79^{c,d}$	499.3^{b}
Growth B × ring A × height B	$2.27^{b,c}$	531.3^{a}
Growth B × ring B × height A	0.95^{e}	$476.0^{b,c}$
Growth B × ring B × height B	1.55^{d}	$465.2^{c,d}$

Means within a given column with the same letter (superscripts a, b, c, d, e) are not significantly different ($P \leq 0.05$) as determined by the Tukey test

RW, ring width; RD, ring density

Variation in the ring density components (RD, ED, LD, D_{max}, and D_{min}) among Taiwan yellow cypress trees (nos. 1–16) is presented in Fig. 4. Inter-ring variation in ring density components of Taiwan yellow cypress trees is shown in Fig. 5. RD in the radial direction slowly decreased from the pith outward to the bark side. Inter-tree height position variation in ring width components of Taiwan yellow cypress is given in Fig. 6.

Average ring density in growth B was significantly higher than that in growth A by *t* test (490.5 vs. 445.7 kg m^{-3}, $P < 0.05$). Average ring density of the ring A group was significantly greater than that of ring B by *t* test (476.6 vs. 443.8 kg m^{-3}, $P < 0.05$). Average ring density of the height A group was significantly higher than that of height B by *t* test (461.7 vs. 454.0 kg m^{-3}, $P < 0.05$). Therefore, the specimens of growth B, ring A, and height A had larger ring density than those of growth A, ring B, and height B, respectively. Combining the results given in the foregoing paragraph, the faster growing trees had greater ring width and smaller ring density than those of slower growing trees. Trees with more than 20 rings produced greater ring width and larger ring density than those trees with 21 rings to the bark side. Tree height at 5.3, 7.3, and 9.3 m above ground created greater ring width and smaller ring density than those of tree height at 0.3, 1.3, and 3.3 m above ground.

Significant difference in average ring density was observed between tree growth by radial position interaction (growth × ring) by one-way ANOVA ($P < 0.01$). Average ring density in the four groups showed the following trend: growth B × ring A (500.4 kg m^{-3}) > growth B × ring B (473.5 kg m^{-3}) > growth A × ring A (460.3 kg m^{-3}) > growth A × ring B (435.5 kg m^{-3}) by Tukey test.

Furthermore, significant difference in average ring density was observed between radial by tree height position interaction (ring × height) by ANOVA ($P < 0.01$). Average ring density in the four groups showed the following trend: ring A × height B (476.7 kg m^{-3}) and ring A × height A (476.6 kg m^{-3}) > ring B × height B (447.2 kg m^{-3}) and ring B × height A (441.5 kg m^{-3}) by Tukey test.

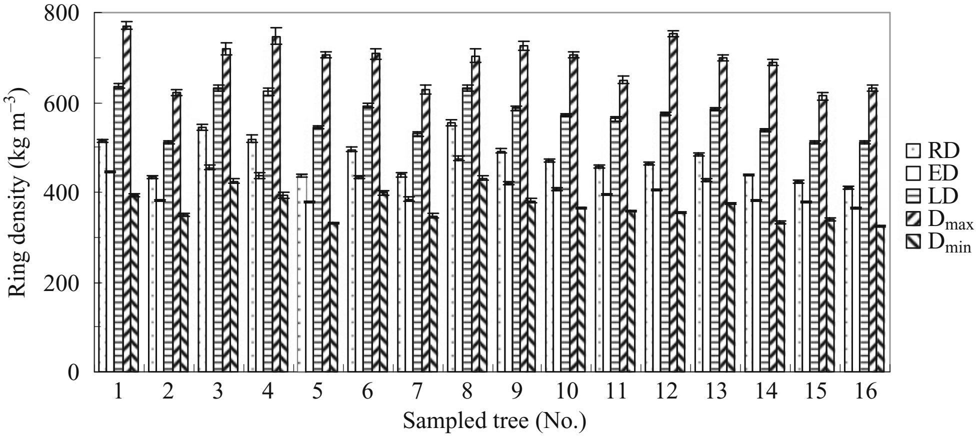


Fig. 4. Inter-tree variation in ring density components based on all rings at all tree heights of naturally regenerated Taiwan yellow cypress trees. *RD*, ring density; *ED*, earlywood density; *LD*, latewood density; D_{max}, maximum density in a ring; D_{min}, minimum density in a ring

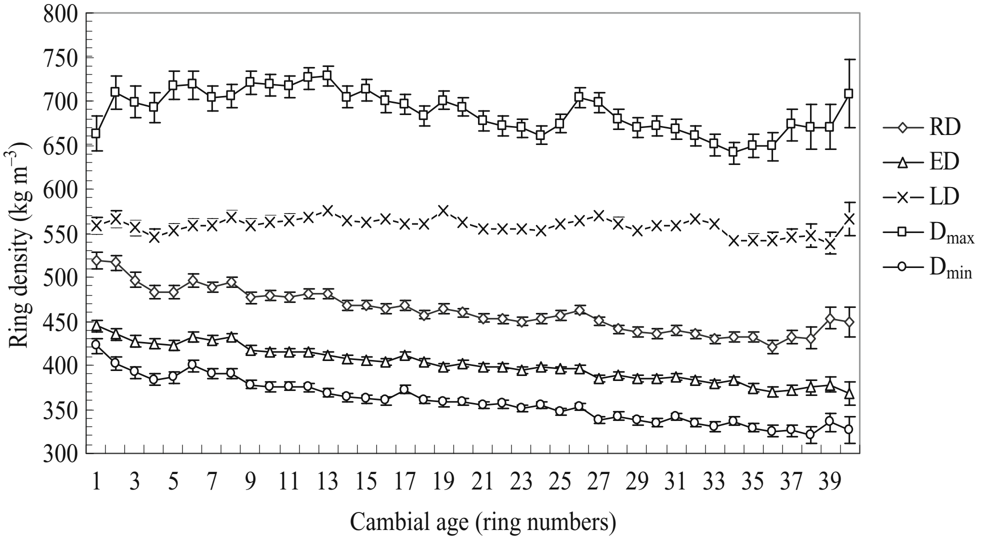


Fig. 5. Inter-ring variation in ring density components based on all rings at all heights of all sampled Taiwan yellow cypress trees. *RD*, ring density; *ED*, earlywood density; *LD*, latewood density; D_{max}, maximum density in a ring; D_{min}, minimum density in a ring

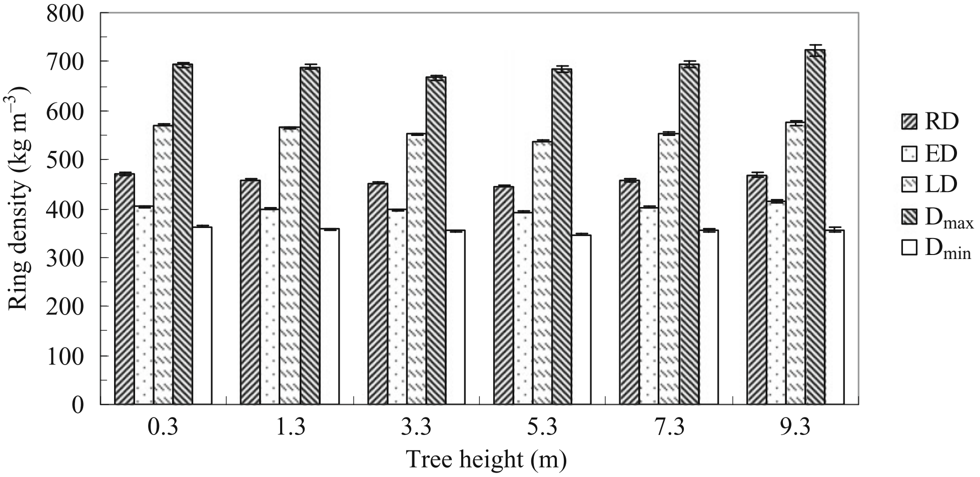


Fig. 6. Inter-tree height positions variation in ring density components based on all rings at all heights of all sampled Taiwan yellow cypress trees. *RD*, ring density; *ED*, earlywood density; *LD*, latewood density; D_{max}, maximum density in a ring; D_{min}, minimum density in a ring

Moreover, significant difference in average ring density was observed among tree growth by tree height position interactions (growth × height) by ANOVA ($P < 0.01$). Average ring density in the four groups showed the following trend: growth B × height A (2.59 mm) and growth B × height B (2.56 mm) > growth A × height B (1.70 mm) and growth A × height A (1.53 mm) by Tukey test. The effects of various tree height positions on ring density were smaller than tree growth features and ring radial positions.

Significant differences in average ring density were observed between tree growth by radial by tree height position interaction (growth × ring × height) by ANOVA ($P < 0.01$). The difference in average ring density for the various groups was analyzed using the Tukey test (see Table 3). Mean ring density of growth B × ring A × height B was the greatest among the eight groups.

In the present work, sampled trees were collected from different ages and sizes, which may be reflected in the variations in ring density components. Regarding radial variation in ring density, Chiu and Lin[24] reported that significant differences in wood density of plantation-grown Taiwan red cypress (*Chamaecyparis formosensis*) were observed between trees and between radial positions. Panshin and de Zeeuw[7] indicated that the radial distribution pattern in wood density variation of *Chamaecyparis lawsoniana* and *C. obtusa* can be classified into type III, decreasing from the pith to the bark. Zobel and Sprague[6] indicated that members of the Cupressaceae (*Chamaecyparis* and *Cupressus*) usually have high wood density near the tree center, which diminishes for a few rings from the pith and then levels off or becomes greater again toward the bark. Koga and Zhang[10] reported that cambial age of balsam fir (*Abies balsamea*) explains more intra-tree variation in wood density components than does ring width, whereas more intra-tree variation in ring width components is the result of ring width. Thus, radial variation in RD may be affected by cambium age.

In this experiment, significant differences in RD were observed between rings by ANOVA; however, the density profile in radial variation did not steeply change (see Fig. 5). Zhu et al.[25] indicated that Douglas-fir grown under various degrees of suppression in a natural forest setting

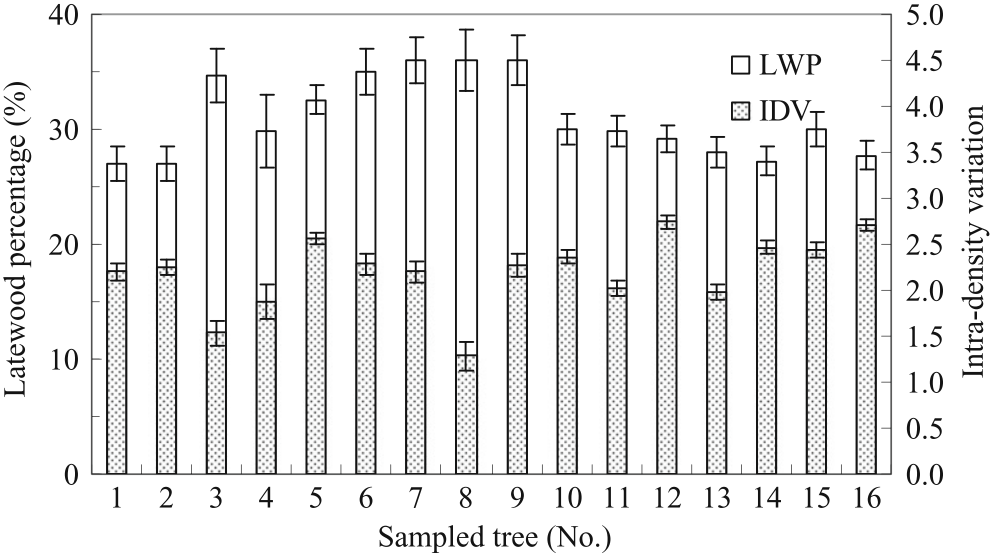


Fig. 7. Inter-tree variation in latewood percentage and intra-ring density variation based on all rings at all heights of all sampled Taiwan yellow cypress trees. *LWP*, latewood percentage; *IDV*, intra-ring density variation

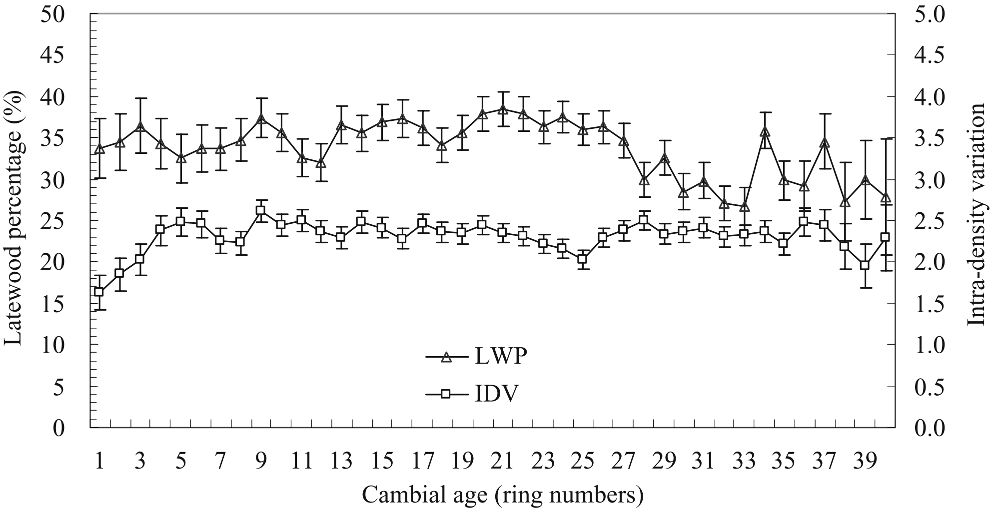


Fig. 8. Inter-ring variation in latewood percentage (*LWP*) and intra-ring density (*IDV*) based on all rings at all heights of all sampled Taiwan yellow cypress trees

may have increased uniformity of wood density in the radial direction. In addition to the radial variation feature of the species in RD, Taiwan yellow cypress trees grew under various degrees of suppression in a natural forest setting, which may have increased the uniformity of RD components within an individual tree. Thus, RD may be affected by environment conditions such as tree competition, plantation spacing, and stand density.

Latewood percentage and intra-ring density variation

Differences in average latewood percentage and intra-ring density variation among sampled trees, rings, and tree height position were analyzed by ANOVA (see Table 2). Significant differences in LWP were observed among trees, rings, and tree height positions. Significant differences in IDV were observed between trees and tree height position; however, no significant difference was found between rings.

Variation in LWP and IDV among Taiwan yellow cypress trees (nos. 1–16) is presented in Fig. 7. Inter-ring variation in LWP and IDV of Taiwan yellow cypress trees is shown in Fig. 8. In sum, LWP in the radial direction showed a constant fluctuation from the pith outward to about the 25th ring and then decreased in irregular fashion to the bark side. IDV in the radial direction increased from the pith outward to about the 5th ring and then remained almost stable continuing toward the bark side. Inter-tree height position variation in LWP and IDV of Taiwan yellow cypress is shown in Fig. 9.

Screw withdrawal resistance

Differences in average screw withdrawal resistance among sampled trees and tree height positions were assessed by ANOVA (Table 4). Significant differences in SWR were observed among trees and tree height positions. Variation in SWR among Taiwan yellow cypress trees (nos. 1–16) is presented in Fig. 10. Inter-tree height position variation in SWR of Taiwan yellow cypress is shown in Fig. 11.

Relationships between ring characteristics

Table 5 shows correlation coefficients for all pairwise comparisons of ring characteristics based on all rings at all heights of all sampled trees. Based on the results of this experiment, ED, LD, D_{max}, D_{min} (density components), and LWP were the most important factors determining the overall RD. The coefficients of relationship (r) were 0.84, 0.67, 0.52, 0.83, and 0.64, respectively ($P < 0.01$). Tree RW (tree growth) did not correlate with tree RD ($r = 0.04$, $P > 0.05$). Moreover, the r values (< 0.45) were low, no matter which specimens came from the different groups (two growth, ring, and height groups, and the interactions). This result indicated that tree growth rates of naturally regenerated Taiwan yellow cypress trees will likely not have a large impact on wood properties, consistent with a previous finding (same species) by Lin et al.[3]

Kennedy,[26] Koga and Zhang,[9] and Zhang[27] reported that wood density generally tended to decrease with increasing RW. However, RD may significantly vary with various ring characteristics, as demonstrated in this study. Koga and Zhang[9] indicated that wood density of balsam fir (*Abies balsamea*) is significantly correlated with its components and with LWP; ED and LWP are the two most important parameters in determining overall wood density. Wood density is not significantly correlated with RW. Taylor and Burton[28] indicated that specific gravity was not significantly influenced by growth rate difference, and Karenlampi and Riekkinen[29] reported that the basic density is independent of growth rate, even if it is negatively correlated with ring width. Thus, the relationship between wood density and annual growth rate (ring width) may vary with cambial age (ring number from pith) and environmental conditions.

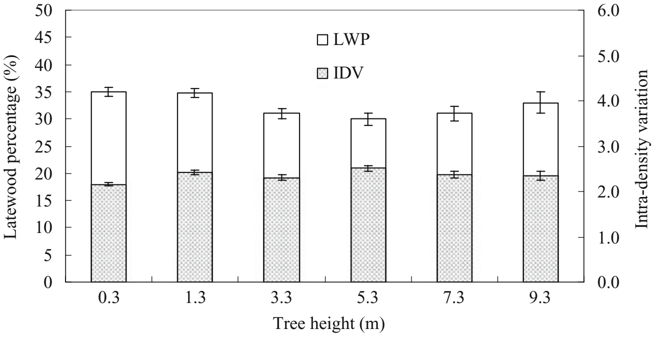


Fig. 9. Inter-tree height positions variation in latewood percentage (*LWP*) and intra-ring density (*IDV*) based on all rings at all heights of all sampled Taiwan yellow cypress trees

Table 4. Results of analysis of variance (ANOVA) for differences in screw withdrawal resistance of Taiwan yellow cypress comparing trees and tree height positions

Variance	Tree	Tree height	Residual	Total
Degrees of freedom	15	5	48	69
Sum of squares	18,971	3,626	12,541	1,525,564
Mean square	1,265	725	261.3	
F value	4.8**	2.8*		

* Significant at 5% level by *F* test
** Significant at 1% level by *F* test

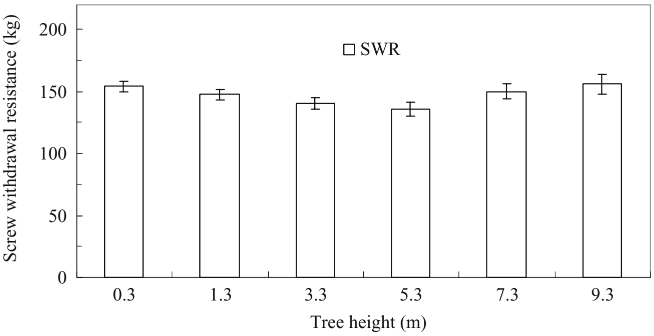


Fig. 11. Inter-tree height positions variation in screw withdrawal resistance (*SWR*) based on all heights of all sampled Taiwan yellow cypress trees

Fig. 10. Inter-tree variation in screw withdrawal resistance (*SWR*) based on all heights of all sampled Taiwan yellow cypress trees

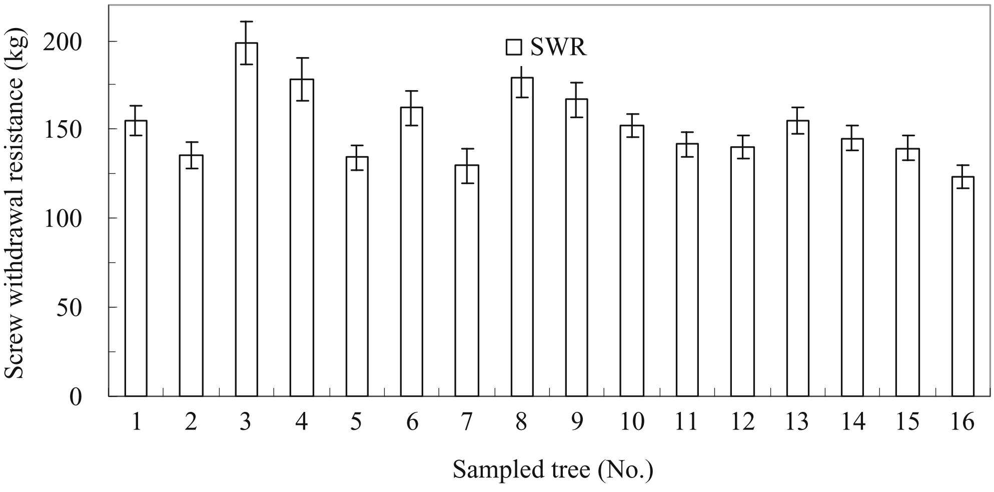


Table 5. Coefficients of relationships between tree ring characteristics of naturally regenerated Taiwan yellow cypress based on all rings at all heights of all sampled trees

Variable	RW	EW	LW	RD	ED	LD	D_{max}	D_{min}	LWP	IDV
RW	1.00	0.76**	0.79**	0.04	0.11**	–0.20**	0.18*	0.06*	0.22**	0.20**
EW		1.00	0.19**	–0.27**	–0.10**	–0.17**	0.11**	–0.22**	–0.35**	0.41**
LW			1.00	0.33**	0.26**	–0.14**	0.17**	0.30*	0.67**	–0.09**
RD				1.00	0.84**	0.67**	0.52**	0.83**	0.64**	–0.37
ED					1.00	0.51**	0.32**	0.93**	0.42**	–0.24
LD						1.00	0.69**	0.41**	0.05	–0.01
D_{max}							1.00	0.25**	0.20**	0.40**
D_{min}								1.00	0.54**	–0.20**
LWP									1.00	–0.39**
IDV										1.00

EW, earlywood width; LW, latewood width; RW, ring width; ED, earlywood density; LD, latewood density; RD, ring density; D_{min}, minimum density in a ring; D_{max}, maximum density in a ring; LWP, latewood percentage; IDV, intra-ring density variation; SWR, screw withdrawal resistance

* Significant at 5% level by *F* test

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

Table 6. Coefficients of relationships between screw withdrawal resistance (SWR) and tree growth characteristics of Taiwan yellow cypress trees based on all heights of all sampled trees

Traits	EW	LW	RW	ED	LD	RD	D_{max}	D_{min}	LWP	IDV
SWR	–0.22	0.21	–0.11	0.67**	0.35**	0.67**	0.12	0.67**	0.52**	–0.46**

EW, earlywood width; LW, latewood width; RW, ring width; ED, earlywood density; LD, latewood density; RD, ring density; D_{min}, minimum density in a ring; D_{max}, maximum density in a ring; LWP, latewood percentage; IDV, intra-ring density variation; SWR, screw withdrawal resistance

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

Dutilleul et al.[30] reported the relationship between RW and RD depends on the growth rate of Norway spruce (a negative relationship in slowly growing trees and no relationship in rapidly growing trees). In this experiment, tree growth rate was faster for about the 1st to 25th rings from the pith than from the 26th to 40th rings (Fig. 1). Koga and Zhang[10] 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, affected by factors such as tree stem position, cambium age, growth traits, genetic factors, and environmental conditions.[2–4]

Relationships between ring characteristics and SWR

Several researchers reported that density or strength properties of wood-based materials are correlated to screw withdrawal strength.[15–19] Hence, SWR is an NDE technique that can be used to estimate wood properties. However, it is difficult to generalize the behavior of woods in radial screw withdrawal because of the complex interaction of various anatomical factors. We were therefore interested in the relationships between screw withdrawal force and tree ring features. Moisture content (MC) affects physical and mechanical properties when it varies below the fiber saturation point (FSP). When MC is reduced, strength increases, and vice versa. Above the FSP, strength properties are constant with changes in MC.[7] The relationship between wood MC and SWR was not investigated in this study. However, in general, the physical and mechanical properties of wood remain fairly constant when MC is above the FSP. The wood MC of a standing tree should be greater than the FSP. Thus, wood properties of different living trees by SWR could be compared in the field (under the same situation).

Table 6 shows the correlation coefficients between ring characteristics and SWR of Taiwan yellow cypress trees. Relationships were positive for SWR with ED, RD, D_{min}, and LWP ($r = 0.67, 0.67, 0.67,$ and 0.52; $P < 0.01$); however, a negative relationship was found for SWR with IDV ($r = 0.46$, $P < 0.01$) by a linear model. SWR was found to be strongly significantly influenced by the RD, rather than the RW, components. In this study, SWR is correlated with ED, RD, D_{min}, LWP, and IDV. Thus, SWR can be used to predict wood density.

Conclusions

1. Significant differences in average RW, EW, LW, RD, ED, LD, D_{max}, D_{min}, and LWP were observed between trees, rings, and tree height positions; differences in average SWR were observed between trees and tree height positions.
2. RW parameters in the radial direction increased from the pith outward to about the 3rd to 5th rings and then decreased to about the 25th ring. The value was almost constantly sustained toward the bark side. Average RW and EW values obtained from a 9.3-m tree height were significantly higher than those at other tree height positions. RD slowly decreased in the radial direction from the pith outward to the bark side. IDV in the radial

direction increased from the pith outward to about the 5th ring and then remained almost stable toward the bark side.

3. The faster grown trees had wider ring width and smaller ring density than those of slower grown trees. Trees with ≤ 20 rings produced wider ring width and larger ring density than trees with >20 rings to the bark side. Tree heights at positions of 5.3, 7.3, and 9.3 m above ground corresponded with wider ring width and smaller ring density than those of tree heights 0.3, 1.3, and 3.3 m above ground.
4. ED, LD, D_{max}, D_{min}, and LWP were the most important factors determining the overall RD. Tree RW (tree growth) did not correlate with tree RD. Thus, tree growth rates of naturally regenerated Taiwan yellow cypress will likely not have a large impact on wood properties.
5. Positive relationships were recorded for SWR with ED, RD, D_{min}, and LWP; however, a negative relationship was found for SWR with IDV by a linear model. In this study, SWR is correlated to ED, RD, D_{min}, LWP, and IDV. Thus, SWR can be used to predict wood density.

Acknowledgments The authors thank the Taiwan Forestry Research Institute for financial support (982101010509-080402G1).

References

1. Chiu CM, Lo-Cho CN, Chung HH (1995) The stem form and crown structure of natural regeneration stands of *Chamaecyparis taiwanensis* in Chi-Lan-Shan area. Bull Taiwan For Res Inst New Ser 10:121–130
2. Yang YC (2007) Crown structures of naturally regenerated *Chamaecyparis obtusa* var. *formosana* in Chi-Lan-Shan. Master's thesis, National I-Lan University, Ilan, Taiwan
3. Lin CJ, Lin ST, Chung CH (2010) Tree ring and wood quality of naturally regenerated *Chamaecyparis obtusa* var. *formosana* stand in Chi Lan-Shan. Q J Chin For 43:131–141
4. Alteyrac J, Cloutier A, Ung CH, Zhang SY (2006) Mechanical properties in relation to selected wood characteristics of black spruce. Wood Fiber Sci 38:229–237
5. Zobel BJ, van Buijtenen JP (1989) Wood variation: its causes and control. Springer-Verlag, Berlin, pp 218–248
6. Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer-Verlag, Berlin, pp 21–22, 26–38, 88–89
7. Panshin AJ, de Zeeuw C (1980) Textbook of wood technology: structure, identification, properties, and uses of the commercial woods of the United States and Canada. McGraw-Hill, New York, pp 269–277
8. Vargas-Hernandez J, Adams WT (1991) Genetic variation of wood density components in young coastal Douglas-fir: implications for tree breeding. Can J For Res 21:1801–1807
9. Koga S, Zhang SY (2002) Relationships between wood density and annual growth rate components in balsam fir (*Abies balsamea*). Wood Fiber Sci 34:146–157
10. Koga S, Zhang SY (2004) Inter-tree and intra-tree variations in ring width and wood density components in balsam fir (*Abies balsamea*). Wood Sci Technol 38:149–162
11. Fujimoto T, Kita K, Kuromaru M (2008) Genetic control of intra-ring wood density variation in hybrid larch (*Larix gmelinii* var. *japonica* × *L. kaempferi*) F_1. Wood Sci Technol 42:227–240
12. Pellerin RF, Ross RJ (2002) Nondestructive evaluation of wood. Forest Products Society, Madison, WI, pp 149–156
13. Forest Products Laboratory (1999) Wood handbook: wood as an engineering material. Gen Tech Rep FPL-GTR-113. Forest Service, U.S. Dept. of Agriculture, Forest Products Laboratory, Madison, WI
14. Cai Z, Hunt MO, Soltis LA (2002) Screw withdrawal: a means to evaluate densities of in situ wood members. Proceedings of the 13th International Symposium on Nondestructive Testing of Wood, August 19–21, 2002, University of California, Richmond, CA, pp 277–281
15. Semple KE, Smith GD (2006) Prediction of internal bond strength in particleboard from screw withdrawal resistance models. Wood Fiber Sci 38:256–267
16. Vassiliou V, Barboutis I (2005) Screw withdrawal capacity used in the eccentric joints of cabinet furniture connectors in particleboard and MDF. J Wood Sci 51:572–576
17. Winandy JE, Lebow PK, Nelson W (1998) Predicting bending strength of fire-retardant-treated plywood from screw-withdrawal tests. Res Pap FPL-RP-568. Forest Service, U.S. Department of Agriculture, Forest Products Laboratory, Madison, WI
18. Wong ED, Zhang M, Wang Q, Kawai S (1999) Formation of the density profile and its effects on the properties of particleboard. Wood Sci Technol 33:327–340
19. Wong ED, Zhang M, Wang Q, Han G, Kawai S (2000) Formation of the density profile and its effects on the properties of fiberboard. J Wood Sci 46:202–209
20. van Laar A, Akca A (2007) Forest mensuration. Springer, Dordrecht
21. QMS (1999) QMS Tree Ring Analyzer Users Guide Model QTRS-01X. Quintek Measurement Systems, Knoxville, TN
22. Guo BZ (1995) Five important softwood species in Taiwan. No. 956, Chinese Forestry Association, pp 206–225
23. Haygreen JG, Bowyer JL (1982) Forest products and wood science: an introduction. Iowa State University Press, Ames, pp 109–110
24. Chiu CM, Lin CJ (2007) Radial distribution of the green moisture content in trunks of 46-year-old red cypress (*Chamaecyparis formosensis*). J Wood Sci 53:374–380
25. Zhu JY, Vahey DW, Scott CT (2008) Some observations of wood density and anatomical properties in a Douglas-fir sample with suppressed growth. Wood Fiber Sci 40:225–232
26. Kennedy RW (1995) Coniferous quality in the future: concerns and strategies. Wood Sci Technol 29:321–338
27. Zhang SY (1995) Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. Wood Sci Technol 29:451–465
28. Taylor FW, Burton JD (1982) Growth ring characteristics, specific gravity, and fiber length of rapidly grown loblolly pine. Wood Fiber 14:204–210
29. Karenlampi PP, Riekkinen M (2004) Maturity and growth rate effects on Scots pine basic density. Wood Sci Technol 38:465–473
30. Dutilleul P, Herman M, Avella-Shaw T (1998) Growth rate effects on correlations among ring width, wood density, and mean tracheid length in Norway spruce (*Picea abies*). Can J For Res 28:56–68