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ORIGINAL ARTICLE

Chih-Ming Chiu · Cheng-Jung Lin

Radial distribution patterns of the green moisture content in trunks of 46-year-old red cypress (*Chamaecyparis formosensis*)

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Abstract Understanding the green moisture content and wood density is important for effective forest management. Radial distribution patterns in the green moisture content (*MC*) and basic density (*BD*) in stems of red cypress (*Chamaecyparis formosensis*) were investigated in 69 plantation trees that were 46 years old. An increment core was collected from each sample tree at breast height (1.3 m). Five radial positions were defined: pith piece (Pith), inner heartwood (IHW), outer heartwood (OHW), intermediate wood (TSH), and sapwood (SW). Results showed that the average *MC* was highly dependent on the individual tree. Average values of the *MC* obtained from the TSH were significantly lower than those for the other positions. The *MC* of heartwood was higher than that of SW. Distribution patterns of the *MC* in the radial direction varied among trees. Radial variations in *MC* and *BD* were greater than in between-tree variations. Six types of radial distribution patterns of *MC* were detected for sample trees. *MC* values increased with decreasing *BD* (except for the TSH). Positive correlations were found between adjacent sampling positions in both *MC* and *BD*.

Key words *Chamaecyparis formosensis* · Green moisture content · Basic density · Radial distribution pattern

Introduction

During the past several years, nondestructive evaluation methods have been extensively applied to standing trees to estimate their physical properties using various techniques.[1,2] However, when applied to living trees and green logs, the nondestructive evaluation parameters (e.g., drilling resistance value and ultrasonic wave velocity) were found to be significantly affected by the moisture content of the tree.[3,4] Therefore, it is important to understand the variability of the green moisture content (*MC*) of trees when estimating the physical properties of standing trees using nondestructive techniques.

Plantation trees of red cypress (*Chamaecyparis formosensis* Matsum) are an important resource for lumber production in Taiwan, and the effective utilization of wood requires understanding of its properties. During the investigation of some fundamental physical properties, an interesting phenomenon was observed at the transverse surface of the trunks of harvested trees. Some dry parts and wet parts were observed in the stem, and the *MC* of the intermediate wood seemed lower than those of the other positions. This phenomenon has also been reported in other conifers.[5,6] The intermediate wood is transitional between sapwood (SW) and heartwood (HW). It is generally known that, in coniferous trees, the *MC* of SW is significantly higher than that of HW.[7,8] However, wetwood is a type of HW in standing trees that has been internally infused with *MC*, and wetwood is higher in *MC* than the adjacent normal HW.[9] Ward[10] reported in a review that wetwood forms in living trees and is an abnormal, water-infused, type of HW that is invariably associated with bacterial infestation.

Haygreen and Bowyer[8] indicated that the *MC* is important because of its direct relation to the weight and processing of the timber and that it varies considerably among species. The *MC* is frequently mentioned in studies dealing with wood products, but no investigation has been conducted on red cypress standing trees. Within any species, there is considerable *MC* variation in trees depending upon the season, soil moisture content, site, age, and growth of the tree.[9] In addition, there are large intertree and intratree (radial and longitudinal) variations in *MC* within a species.[6–8,11–13] Nakada et al.[14] indicated that distribution patterns of the *MC* in the longitudinal direction varied among trees of *Cryptomeria japonica*. Variations in patterns were similar among individual trees of the same cultivar, but not among cultivars. Iizuka et al.[5] explored statistical differ-

C.-M. Chiu
Division of Forest Management, Taiwan Forestry Research Institute, Taipei 100, Taiwan

C.-J. Lin (✉)
Division of Forest Utilization, Taiwan Forestry Research Institute, 53 Nan-Hai Rd., Taipei 100, Taiwan
Tel. +886-22-303-9978 (ext. 2604); Fax +886-22-303-5738
e-mail: d88625002@yahoo.com.tw

ences in tree growth, *MC*, and basic density (*BD*) of HW and SW between *Abies sachalinensis* sample clones.

In addition to the *MC*, the density of wood is its single most important physical characteristic, and most mechanical properties of wood are closely correlated to wood density.[8] Moreover, knowledge of the wood density is useful for estimating shipping weights. However, the density of wood varies between species, environmental conditions, silvicultural practices, and other factors. Furthermore, pith-to-bark radial variations in wood density exhibit different types of radial distribution patterns, which vary among trees and species.[15,16]

The aim of this study was to provide information for forest managers and sawmill operators about the *MC* and *BD* of red cypress timber. Therefore, the main objective of this study was to investigate the radial distribution of the *MC* in stems of red cypress. Secondary objectives were to calculate variations in the *BD* for comparison and to explore the relationship between *MC* and *BD*.

Material and methods

The study site was located at an elevation of 1500 m in the No. 4 forest compartment, Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaohsiung County, southwestern Taiwan. The mean annual temperature is 17.06°C, relative humidity is 86%, and precipitation is 3706 mm. Most of the annual rainfall occurs from May to September.

All sample trees of red cypress came from seeds obtained from one provenance (population). The area of the study site, about 12 ha, was planted with red cypress at a stocking rate (initial spacing) of 2500 trees/ha in 1957. A thinning was implemented at a stocking rate of 1000 trees/ha in 1983. The mean diameter at breast height (DBH) was 25 cm, tree height was 17 m, the stocking rate was 800 trees/ha, and volume was 300 m^3/ha in 2002. Sixty-nine trees (number of trees sampled) of red cypress were chosen. General information on the sampled trees is shown in Table 1.

An increment borer was used to remove 10-mm-diameter cores from the trees. From the east side of each sample tree, we extracted a pith-to-bark increment core specimen at breast height in April 2004, when the trees were about 46 years old.

As shown in Fig. 1, five radial sections of the core were separated by position: sapwood (SW), intermediate wood (TSH), outer heartwood (OHW), inner heartwood (IHW), and a pith piece (Pith). Wang[17] indicated that HW was light reddish brown, distinguishable from the sapwood, which is narrow and light pinkish white.

Between SW and HW, a narrow (about 1–4 mm) band of light yellowish white was observed. This band differed distinctly from the colors of the SW and HW and is considered to be the TSH. In this experiment, TSH is defined as an area between two lines drawn at 5 mm to the left and 5 mm to the right from the center of the TSH.

All cores were extracted from sampled trees in the field, then immediately cut into five sections and wrapped in plastic (sealed in Ziploc storage bags, SC Johnson, Racine, WI, USA) to prevent loss of moisture. Afterward, the cores were transferred to the laboratory for measurements.

The volumes of the sample cores were measured by the water displacement method,[8] and so the *BD* was calculated as the ratio of its oven-dry weight (105°C) to the weight of the displaced water.[18–20]

The green moisture content (*MC*) and basic density (*BD*) were calculated from the following formulas:[14]

$$MC(\%) = [(Wg - Wo)/Wo] \times 100, \quad (1)$$

$$BD(\text{g/cm}^3) = Wo/Vg, \quad (2)$$

$$Vg = (Ws - Ww)/r, \quad (3)$$

where Wg is the green weight (g), Wo is the oven-dry weight (g), Vg is the green volume (cm^3), Ws is the weight of water-saturated wood (g), Ww is the weight of water-saturated wood in water (g), and r is the water density. In this experi-

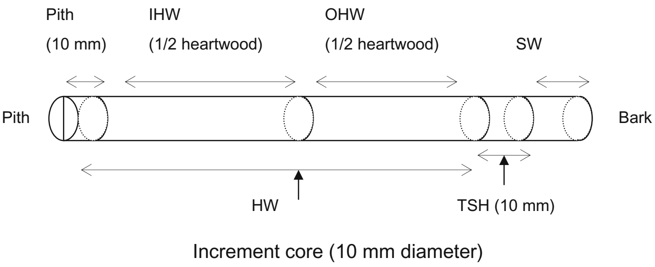

Fig. 1. Scheme of core sample cutting in a standing tree and illustration of the radial positions. Five radial sections of core were: pith piece (*Pith*), from the pith outward by 1 cm; intermediate wood (*TSH*), an area between two lines drawn 5 mm to the left and 5 mm to the right of the center of the intermediate wood; heartwood (*HW*), from the Pith border outward to the TSH inside border; inner heartwood (*IHW*), inside half of the HW width; outer heartwood (*OHW*), outside half of the HW width; sapwood (*SW*), from TSH outside border outward to the bark side

Table 1. General characteristics of the 69 red cypress trees sampled

	DBH (cm)	*H* (m)	Cw (m)	BLc (m)	Sw (cm)
Minimum	15.8	15.5	1.6	5.0	1.5
Maximum	37.1	20.5	4.8	11.0	4.9
Mean	26.5	17.8	3.18	7.84	2.94
SD	3.62	1.01	0.64	1.47	0.63
CV (%)	13.7	5.7	20.1	18.8	21.4

DBH, diameter at breast height (1.3 m); *H*, tree height; Cw, crown width; BLc, crown base height; Sw, sapwood width; SD, standard deviation; CV, coefficient of variation ment, the *MC* and *BD* were individually calculated for the five radial positions.

Analysis of variance (ANOVA) was used to determine if the tree and radial position factors significantly affected the *MC* and *BD*. *F* values were computed to test for significance. When the tree and radial position effects were significant, means were compared using Duncan's multiple-range test.[21]

Results

Table 2 provides some basic statistics concerning variations in *MC* and *BD* in the 69 sampled cores. The average *MC* values covered a fairly wide range of from 102.9% to 208.5%, with a mean of 147.7%. The mean *BD* of sample cores was 0.392 g/cm^3 (range 0.337–0.432 g/cm^3). From these elementary results, it appears that individual samples had important effects on the observed variability.

The ANOVA results of the *MC* of various trees and five radial positions are shown in Table 3. Significant differences in the *MC*s were observed between trees and between the five radial positions. As shown in Table 3, the radial variation component contributed 37.8%, while the between-tree variance component had a lower contribution (21.6%) to the total variation in red cypress.

Differences in *MC* for the five radial positions were analyzed using Duncan's test, and results are shown in Table 4. It was found that the average values of the *MC* obtained from TSH were significantly lower than those for the other positions. However, there was no significant difference among the IHW, Pith, and OHW. Therefore, this study indicated that variations in *MC* showed the following trend: IHW, Pith, OHW > SW > TSH. Three Duncan's groups at $P < 0.05$ could clearly be differentiated. TSH, considered to be HW formation in progress, was consistently found in sample trees. In this experiment, the mean distance from the pith to the boundary between HW and TSH was 10.02 cm [i.e., mean HW width was 20.04 cm, standard deviation (SD) 2.18 cm] in red cypress trees and HW contained about 26–32 ring numbers. The mean SW width was 2.94 cm (SD 0.63 cm) at breast height. The mean DBH value of sampled trees was 26.5 cm (46 years old) (Table 1).

The mean *MC* in the transverse direction increased from the Pith outward to the IHW, and then decreased toward the outer TSH. Finally, the *MC* tended to increase toward the SW. In this study, distribution patterns of the

Table 2. Descriptive statistics of the green moisture content (*MC*) and basic density (*BD*) in the 69 red cypress trees sampled

Items	Minimum	Maximum	Mean	SD	CV (%)
MC (%)	102.9	208.5	147.8	28.69	19.4
BD (g/cm^3)	0.337	0.432	0.392	0.0393	10.0

Table 3. Results of analysis of variance tests for differences in the green moisture content and basic density between trees and the five radial positions

Source	DF	Green moisture content				Basic density			
		MS	*F* value	Variance component	Contribution to total variance (%)	MS	*F* value	Variance component	Contribution to total variance (%)
Tree	68	3013.6	3.66**	438.1	21.6	0.003234	2.09**	0.000337	14.6
Position	4	53683.8	65.23**	766.1	37.8	0.03047	19.68**	0.000419	18.2
Error	272	823.0		823.0	40.6	0.001548		0.001548	67.2
Total	344			2027.2	100			0.002304	100

DF, degrees of freedom; MS, mean squares

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

Table 4. Comparison of the average green moisture content and basic density according to the radial position at breast height

Radial position	Green moisture content (%)	Basic density (g/cm^3)
Pith	167.0 a	0.380 c
IHW	172.4 a	0.385 bc
OHW	159.1 a	0.370 c
TSH	104.5 c	0.399 b
SW	136.1 b	0.424 a

Means within a given row with the same letter do not significantly differ ($P \leq 0.05$), as determined by Duncan's multiple-range test

IHW, inner heartwood; Pith, pith piece; SW, sapwood; OHW, outer heartwood; TSH, intermediate wood

MC in the five radial positions varied among trees. However, these six types of radial distribution patterns are defined as follows:

- Type /: the *MC* gradually increased from the Pith to the SW;
- Type \: the *MC* gradually decreased from the Pith to the SW;
- Type V: the *MC* in the radial direction decreased from the Pith outward to the TSH, and then increased toward the SW;
- Type Λ: the *MC* in the radial direction increased from the Pith outward to the OHW, and then decreased toward the SW;
- Type N: the *MC* in the radial direction increased from the Pith outward to the OHW, and then decreased to the TSH. Finally, it increased toward the SW; and,
- Type W: the *MC* in the radial direction decreased from the Pith to the IHW, and then increased to the OHW. Then it decreased to the TSH, and, finally, it increased toward the SW.

The radial distribution patterns can be classified into six types on the basis of the changing formation, namely, type / (3 trees, 4.3%), type \ (5 trees, 7.2%), type V (25 trees, 36.2%), type Λ (7 trees, 10.1%), type N (24 trees, 34.8%), and type W (5 trees, 7.2%). The results indicated that most trees were of types V and N (71%). The radial distribution patterns in the average *MC* in all sampled trees are shown in Fig. 2.

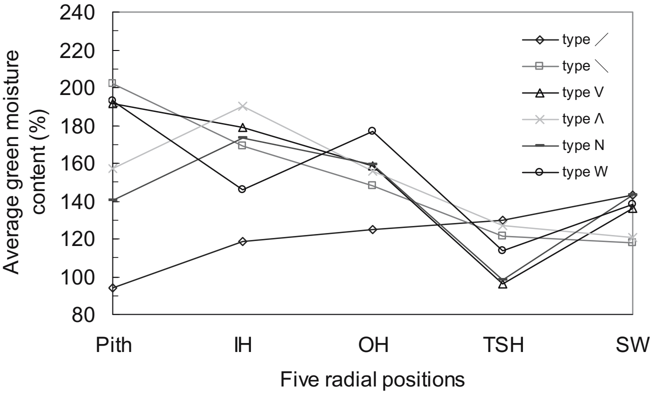

Fig. 2. Radial distribution patterns of average green moisture content for the five radial positions

The ANOVA results of the *BD* of various trees and five radial positions are shown in Table 3. Significant differences in the *BD* were observed between trees and between the five radial positions.

As shown in Table 3, the radial variation component contributed 18.2%, while the between-tree variance component had a smaller contribution (14.6%) to the total variation in red cypress. Therefore, the within-tree variance component contributed more to the total variation than did the between-tree variance component in this study.

In this experiment, differences in the *BD* for the five radial positions were analyzed using Duncan's test, and results are shown in Table 4. It was found that the average values of the *BD* obtained from SW were significantly higher than those for the other positions. Results of this study indicated that variations in *BD* showed the following trend: SW > TSH > IHW > Pith > OHW. However, there were no significant differences between TSH and IHW, or among IHW, Pith, and OHW.

All sampled trees came from seeds obtained from one provenance, and no further genetic analysis was conducted. Relationships between *MC* and *BD* from the Pith, IHW, OHW, TSH, and SW were examined using simple correlation analyses. Correlation coefficients among wood variables are shown in Table 5. Results show that *MC* values increased with decreasing *BD* (except for the TSH).

In addition, there were positive significant correlations between adjacent sampling positions in both *MC* and *BD* (i.e., between Pith and IHW, IHW and OHW, OHW and TSH, and TSH and SW). These results indicate that the properties of adjacent radial positions are closely correlated. Although their correlation coefficients (*r*) were low, significant differences existed according to the *F*-test (Table 5).

Discussion

The mean value of the *BD* in this study was similar to the result (0.389 g/cm^3) of Wang[17] for this species. Significant variations in the *MC*s were observed among trees and among the five radial positions. These results are similar to those reported by Iizuka et al.,[5] Tsoumis,[7] Constant et al.,[13] and Nakada et al.[14] Statistical differences in *MC*s between trees, within a tree, and between clones were determined

Table 5. Correlation coefficients among the wood variables

Variables	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
X1 *BD* Pith										
X2 *BD* IHW	0.28*									
X3 *BD* OHW	–0.10	0.28*								
X4 *BD* TSH	0.10	0.10	0.57**							
X5 *BD* SW	–0.14	0.10	0.49**	0.57**						
X6 *MC* Pith	–0.37**									
X7 *MC* IHW		–0.50**				0.62**				
X8 *MC* OHW			–0.47**			0.42**	0.53**			
X9 *MC* TSH				0.17		0.22	0.22	0.47**		
X10 *MC* SW					–0.71**	0.14	0.33**	0.42**	0.35**	

* Significant at the 5% level; ** significant at the 1% level by the *F*-test

by analysis of variance. Fujisawa et al.[22] and Nakada et al.[23,24] reported that the *MC* distribution in HW varied among individual sugi (*Cryptomeria japonica*) trees. Moreover, the variation in *MC* of the trees may have been affected by the environmental conditions of the site and silvicultural practices, as well as other factors.[11,16]

The within-tree variance component contributed more to the total variation than did the between-tree variance component in this study. In general, within-tree variations in wood properties are greater than between-tree variations.[18]

In conifers, the *MC* of HW is generally much lower than that of SW,[7,8] and the bordered pits in HW are aspirated due to *MC* loss during HW formation.[6] Haygreen and Bowyer[8] indicated that SW also serves to conduct water upward in a living tree, but HW no longer has this function. Moreover, HW may contain various chemical compounds (which make it a darker color) that are products of decomposition, such as extractives and resins.[7,11,19]

Matsumura et al.[25] indicated that there was no relationship between the green *MC* and the percentage of aspirated pits. It is generally accepted among tree physiologists that water in living trees is transported primarily in response to negative pressures that occur in the leaves due to transpiration of water vapor to the atmosphere.[26] Ward[10] reported that low longitudinal gas permeability values and slow drying rates for HW and wetwood are due largely to the aspiration of bordered pits in white fir tracheids and to tylose formation in aspen vessels.

Attack by wood-degrading fungi (e.g., *Stereum sulcatum*) appears to be common in living stems of old Taiwanese red cypress,[27] and decayed HW (centered pathology, internal cavity) is often found near the ground. In general, the decayed wood has higher *MC* than does sound wood. Therefore, the sampled trees may be infected by fungi in the initial stage of decay (sampled cores at DBH near the ground). Zabel and Morrell[28] indicated that a cross section through a portion containing stem decay often shows all decay stages, ranging from none in the outer sapwood to complete wood removal in the HW. Ward and Pong[9] indicated that wetwood or sinker stock was a condition (bacterial infection) that developed in living trees and caused entire boards or parts of boards to be higher in initial *MC*, to be slower drying, or to be more susceptible to drying defects. Bacterially infected wood often has a disagreeable odor. Ward and Pong[9] and Ward[10] reported in a review that wetwood in trees has been attributed to a number of causes: microbial (bacterial growth), nonmicrobial (natural and silvicultural injuries), and normal age–growth formation. Moreover, causes of wetwood formation include bacterial inflection; physical, mechanical, and biological injuries; species; age; site; and cultural practices.

The sampled cores were extracted in April (the dry season), so the large difference in HW and SW green *MC*s may partly have been due to seasonal variations. Shupe et al.[29] reported that the eastern cottonwood tree they investigated was harvested in the winter, so a large difference in innerwood (170.4%) and outerwood (67.7%) green *MC*s was detected. Kravka et al.[30] stated that the *MC* in SW is not constant and varies both according to time of day and season of the year. The variation in the *MC* in the SW of living trees seems to be controlled in two ways: by variations in pressure, resulting from transpiration demands, and by the *MC* demand of living parenchyma cells, especially those of rays.

Chen et al.[6] and Nakada et al.[14] found that both wet parts and dry parts were present in the stems of sugi trees. The dry parts occur in the TSH (SW adjacent to the boundary of the HW). They indicated that the degree of saturation in the dry part was only one half to one third that of the wet part. Ward and Pong[9] reported that wetwood occurs in both conifers and hardwoods, but its frequency can vary with species, age, and growing conditions of the trees. It is generally known that in coniferous trees, the *MC* of SW is significantly higher than that of HW. Iizuka et al.[5] and Nakada et al.[14] reported that average *MC*s of SW were higher than those of HW in *Abies sachalinensis* and *C. japonica*, respectively.

Nakada et al.[23] indicated that the *MC* of HW was generally unevenly distributed, and three levels of *MC* were distinguishable: wet areas, dry areas, and moderately moist areas. Nakada et al.[24] indicated that five basic types of wet area distribution patterns were distinguishable.

In this experiment, significant differences in *BD* were observed between trees and between the five radial positions. Those results are similar to those reported by Tsoumis,[7] Haygreen and Bowyer,[8] and Koga and Zhang,[31] all of whom indicated that variations in *BD* exist among and within trees.

Wood variation occurs within a tree from the center outward (e.g., juvenile and mature wood), but also from tree to tree, and from the base of the tree to its top. Moreover, wood characteristics within the juvenile zone are not uniform but rapidly change from the pith outward. The area of rapid change is in juvenile wood, while almost no change occurs in mature wood.[7,8]

In this study, intratree variations in *BD* were greater than intertree variations. This finding is similar to that reported earlier by Chiu et al.,[32] who indicated that intratree variations in crushing strength were greater than intertree variations. Zobel and van Buijtenen[15] stated that variability in wood characteristics was greater within a single tree than among trees growing on the same site.

Panshin and de Zeeuw[19] 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. *Chamaecyparis lawsoniana* and *Chamaecyparis obtusa*). Zobel and Sprague[16] indicated that members of the Cupressaceae (*Chamaecyparis* and *Cupressus*) usually have a high wood density near the tree center that diminishes for a few rings from the pith, and then levels off or becomes greater again toward the bark. Itoh et al.[33] reported that the variation in *BD* of *C. obtusa* in the transverse direction could be expressed by two patterns. In pattern I, *BD* was smaller near the pith and bark than other positions in the trunk. In pattern II, the variation showed a trend opposite to that of pattern I. However, Hong[34] reported that red cypress trees appeared to contain all three types[19] of variations. Wang and Hsieh[35] reported that the variation of wood density in the transverse direction could be expressed by two types for red cypress. Their characteristics showed that: (1) wood density was high near the pith, decreases outward for the first few years, and then increases to a maximum near the bark; and (2) wood density increases gradually in the increment near the pith then remains more or less constant, or sometimes the wood density decreases in the last-formed increment near the bark. Therefore, red cypress does display several types of variations.

The basic density of trees may be affected by the environmental conditions of the site, silvicultural practices, tree height positions, anatomical properties, and extractive compositions.[15,16,34,36–38] In this experiment, the position of OHW was at about the 25th to 32nd annual rings (i.e., ring numbers from the pith) in red cypress tree. In 1983, thinning was performed when the trees were about 26 years old. The sample trees grown at a relatively wider spacing had wider annual ring widths and lower densities after thinning. In other words, the mean *BD* of the outer HW may have mainly been affected by the thinning treatment. Therefore, in this study, the variation in the mean *BD* in the transverse direction increased from the Pith outward to the IHW, and then decreased toward the OHW. Finally, the *BD* tended to increase toward the SW.

Water is found in a living tree in two forms: as liquid water in cell walls (bound water) and as liquid and/or vapor in cell cavities (free water). Tsoumis[7] indicated that the maximum *MC* that wood may contain, when both cell walls and cell cavities are saturated, depends on the space available in its mass; there was a negative relationship between the maximum moisture content and *BD*, and the relationship between *MC* and *BD* was shown using Eq. 4:[7]

$$\text{Maximun } MC(\%) = 100/BD - 67. \tag{4}$$

In this study, the *MC* decreased with increasing *BD* (except for TSH in Table 5), although the correlation coefficients were small. Therefore, the influence of *BD* on the *MC* was an important factor, and the *BD* may be further affected by anatomical traits, climatic factors, the chemical composition (extractives), and other complex ecological variables.[7,8]

Conclusions

The green moisture content (*MC*) and basic density (*BD*) are closely correlated to other properties and utilization of the wood. In this study, the *MC* and *BD* in the stems of red cypress (*Chamaecyparis formosensis*) were investigated. The results are summarized as follows:

1. Statistical differences in the *MC* and *BD* between trees and between the five radial positions within individual trees were found. Variations in *MC* showed the following trend: inner heartwood (IHW), pith piece (Pith), and outer heartwood (OHW) > sapwood (SW) > intermediate wood (TSH). The *MC* of heartwood was higher than that of SW, and the *MC* of TSH was significantly lower than those of the other positions.
2. Radial variations in *MC* and *BD* were greater than intertree variations. Six types of radial distribution patterns of *MC* could be discerned for sampled trees.
3. The *MC* values increased with decreases in *BD* (except for the TSH). Positive correlations were found between adjacent radial positions in both *MC* and *BD*.

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References

1. Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD (2001) Nondestructive evaluation of standing trees with a stress wave method. Wood Fiber Sci 33:522–533
2. Pellerin RF, Ross RJ (2002) Nondestructive evaluation of wood. Forest Products Society, Madison, WI, pp 149–168
3. Lin CJ, Wang SY, Lin FC, Chiu CM (2003) Effect of moisture content on the drill resistance value in Taiwania plantation wood. Wood Fiber Sci 35:234–238
4. Wang SY, Lin CJ, Chiu CM (2003) The adjusted dynamic modulus of elasticity above the fiber saturation point in Taiwania plantation wood by ultrasonic-wave measurement. Holzforschung 57:547–552
5. Iizuka K, Oribe Y, Ubukata M (2000) Clonal variation of the green moisture content in grafted plus-trees of *Abies sachalinensis* (in Japanese). Mokuzai Gakkashi 46:397–405
6. Chen YS, Huang YS, Chen SS (1998) A study on moisture distribution of green wood and variations of specific gravity in *Cryptomeria japonica* D. Don. Taiwan J For Sci 13:91–100
7. Tsoumis G (1991) Science and technology of wood – structure, properties, utilization. Van Nostrand Reinhold, New York, pp 111–133
8. Haygreen JG, Bowyer JL (1982) Forest products and wood science – an introduction. Iowa State University, Ames, pp 109–110, 157–170, 196–214
9. Ward JC, Pong WY (1980) Wetwood in trees: a timber resource problem. General technical report PNW-112, Pacific Northwest Forest and Range Experiment Station, US Department of Agriculture Forest Service, Portland, pp 1–56
10. Ward JC (1986) The effect of wetwood on lumber drying times and rates: an exploratory evaluation with longitudinal gas permeability. Wood Fiber Sci 18:288–307
11. Koch P (1972) Utilization of the southern pines, agriculture handbook no. 420, the raw material. Southern Forest Experiment Station, US Department of Agriculture Forest Service, Asheville, pp 235–264
12. Kamaguchi A, Nakao T, Nakai T, Tamura A (2001) Measurement of heartwood moisture content of sugi by the lateral impact vibration method: comparison with data obtained from the moisture meter method and measurement of longitudinal distribution (in Japanese). Mokuzai Gakkashi 47:235–241
13. Constant T, Nepveu G, Huber F (2002) Intra- and inter-tree variability of moisture content in standing sessile oak (*Quercus petraea* Liebl.). Holzforschung 56:117–124
14. Nakada R, Fujisawa Y, Hirakawa Y, Yamashita K (1998) Longitudinal change of the green moisture content in the stem of *Cryptomeria japonica* D. Don (in Japanese). Mokuzai Gakkashi 44:395–402
15. Zobel BJ, van Buijtenen JP (1989) Wood variation – its cause and control. Springer, Berlin Heidelberg New York, pp 72–131

16. Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer, Berlin Heidelberg New York, pp 21–112
17. Wang SY (1983) Commercial timber (in Chinese). Taiwan Forest Products Association, Taipei, pp 71–72
18. Lee CH, Wahlgren HE (1979) Specific gravity sampling with minimal tree damage – a study of red pine. Wood Sci 11:241–245
19. 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
20. Yanchuk AD, Kiss GK (1993) Genetic variation in growth and wood specific gravity and its utility in the improvement of interior spruce in British Columbia. Silvae Genet 42:141–148
21. Anonymous (1982) SAS user's guide: statistics. SAS Institute, Cary, pp 119–138
22. Fujisawa Y, Ohta S, Nishimura K, Toda T, Tajima M (1995) Variation in moisture contents of heartwood among clones and test stands in Sugi (*Cryptomeria japonica*) (in Japanese). Mokuzai Gakkaishi 41:249–255
23. Nakada R, Fujisawa Y, Hirakawa Y (1999) Soft X-ray observation of water distribution in the stem of *Cryptomeria japonica* D. Don I: general descriptions of water distribution. J Wood Sci 45:188–193
24. Nakada R, Fujisawa Y, Hirakawa Y (1999) Soft X-ray observation of water distribution in the stem of *Cryptomeria japonica* D Don II: types found in wet-area distribution patterns in transverse sections of the stem. J Wood Sci 45:194–199
25. Matsumura J, Yamasaki Y, Oda K, Fujisawa Y (2005) Profile of bordered pit aspiration in *Cryptomeria japonica* using confocal laser scanning microscopy: pit aspiration and heartwood color. J Wood Sci 51:328–333
26. Skaar C (1988) Wood–water relations. Spring, Berlin Heidelberg New York, pp 20–22
27. Liu TR, Liao RJ (1979) Dendrology (in Chinese). Commercial, Taipei, pp 144–145
28. Zabel RA, Morrell JJ (1992) Wood microbiology – decay and its prevention. Academic, San Diego, pp 170–171
29. Shupe TF, Choong ET, Gibson MD (1995) Differences in moisture content and shrinkage between innerwood and outerwood of a single cottonwood tree. Forest Prod J 45:89–92
30. Kravka M, Krejzar T, Cermak J (1999) Water content in stem wood of large pine and spruce trees in natural forests in central Sweden. Agr Forest Meteorol 98/99:555–562
31. 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
32. Chiu CM, Wang SY, Lin CJ, Yang TH, Jane MC (2006) Application of the fractometer for crushing strength: juvenile–mature wood demarcation in Taiwania (*Taiwania cryptomerioids*). J Wood Sci 52:9–14
33. Itoh T, Yamaguchi K, Kuroda H, Shimaji K, Sumiya K (1980) Effects of plantation spacing on the wood quality of Sugi and Hinoki trees. Wood Res 15:45–49
34. Hong KJ (1989) Study on the anatomical and physical properties of *Chamaecyparis formosensis* Matsum (in Chinese). PhD thesis, Department of Forestry, National Taiwan University, Taipei, pp 155–156
35. Wang SY, Hsieh TY (1987) Studies on the fundamental properties of the economical tree species in Taiwan (I). The variability of specific gravity, shrinkage, and fiber saturation point of Taiwan yellow cypress, Taiwan red cypress and hemlock (in Chinese). Taiwan Q J Chin For 20:9–25
36. Wellwood RW, Jurazs PE (1968) Variation in sapwood thickness, specific gravity, and tracheid length in western red cedar. Forest Prod J 18:37–46
37. McKimmy MD, Campbell RK (1982) Genetic variation in the wood density and ring width trend in coastal Douglas-fir. Silvae Genet 31:43–51
38. DeBell DS, Singleton R, Harrington CA, Gartner BL (2002) Wood density and fiber length in young populus stems: relation to clone, age, growth rate and pruning. Wood Fiber Sci 34:529–539