Ann. For. Sci. 66 (2009) 611
© INRA, EDP Sciences, 2009
DOI: 10.1051/forest/2009048

Available online at:
www.afs-journal.org

Original article

Use of wood shrinkage characteristics in breeding of fast-grown *Acacia auriculiformis* A. Cunn. ex Benth in Vietnam

Phi H. HAI[1,2]*, Gunnar JANSSON[1,3], Björn HANNRUP[3], Chris HARWOOD[4], Ha H. THINH[2]

[1] Department of Plant Biology and Forest Genetics, Swedish University of Agricultural Sciences, Box 7080, 75007 Uppsala, Sweden
[2] Research Centre for Forest Tree Improvement, Forest Science Institute of Vietnam, Dong Ngac, Tu Liem, Ha Noi, Vietnam
[3] Skogforsk (The Forestry Research Institute of Sweden), Uppsala Science Park, 75183 Uppsala, Sweden
[4] CSIRO Sustainable Ecosystems, Private Bag 12, 7001 Hobart, Australia

(Received 11 December 2008; accepted 12 March 2009)

Keywords:
***Acacia auriculiformis* /**
shrinkage /
within-tree variation /
genotypic coefficient of variation /
repeatability /
genetic correlation

Abstract

- Genotypic variation in wood total and partial shrinkage, basic density and growth traits was estimated in $5^{1}/_{2}$ year old *Acacia auriculiformis* trees in a clonal test.
- In the tangential, radial and longitudinal directions, the mean values were 2.64%, 1.64% and 0.77% for partial shrinkage, and 5.92%, 3.23%, and 0.96% for total shrinkage, respectively. Total and partial transverse shrinkage were significantly greater in sapwood than in heartwood.
- Clonal repeatability (H^2_{C}) estimates for partial shrinkage were lower than those for total shrinkage, and heartwood shrinkages had lower H^2_{C} than those for sapwood. Estimates of H^2_{C} were from 0.32 to 0.38 for total transverse shrinkage, comparable to H^2_{C} for both total and partial volumetric shrinkages (0.40 and 0.32, respectively). However, H^2_{C} for longitudinal shrinkages, total and partial coefficients of anisotropy were only from 0.09 to 0.18.
- The genotypic coefficients of variation of all shrinkage traits varied from 5.45% to 8.02%. Total shrinkage was strongly positively correlated with partial shrinkage in each dimension. Genotypic correlations were not significant between shrinkage and growth traits or density. Strong and significant correlations between transverse shrinkage in heartwood and sapwood (0.87) indicated that juvenile shrinkage is a good genetic indicator of this trait in older trees.

Utilisation du retrait du bois dans l'amélioration de *l'Acacia auriculiformis* A. Cunn. ex Benth à croissance rapide au Vietnam.

Mots-clés :
***Acacia auriculiformis* /**
retraits /
variation intra-arbre /
coefficient de variation génotypique /
répétabilité /
corrélation génétique

Résumé – Utilisation du retrait du bois dans l'amélioration de *l'Acacia auriculiformis* A. Cunn. ex Benth à croissance rapide au Vietnam.

- Nous avons estimé la variation génotypique, des retraits partiels et totaux, de la densité du bois ainsi que des traits de croissance dans un test clonal d'*Acacia auriculiformis* âgé de cinq ans et demi.
- Les retraits partiels (à 12 % d'humidité) dans les directions tangentielle, radiale et longitudinale sont respectivement de 2,64 %, 1,64 % et 0,77 % tandis que les retraits totaux (à l'état anhydre) sont respectivement de 5,92 %, 3,23 % et 0,96 %. Les retraits partiels et totaux transverses sont significativement plus élevés dans l'aubier que dans le bois de cœur.
- Les estimations de la répétabilité clonale (H^2_{C}) pour les retraits partiels sont plus faibles que celles obtenues pour les retrait totaux et les retraits du bois de cœur ont une plus faible (H^2_{C}) que ceux de l'aubier. Les estimations de (H^2_{C}) sont de 0,32 et 0,38 pour le retrait transverse total, valeurs comparables à (H^2_{C}) pour les retraits volumétriques total et partiel (respectivement 0,4 et 0,32). Cependant (H^2_{C}) pour les retraits longitudinaux total et partiels ainsi que pour les coefficients d'anisotropie total et partiels, varient seulement de 0,09 à 0,18.
- Les coefficients génotypique de variation de tous les types de retraits varient de 5,45 % à 8,42 %. Les retraits totaux sont fortement corrélés positivement avec les retraits partiels de chaque direction. Les corrélations génotypiques entre les retraits et les traits de croissance ou la densité ne sont pas significatives. Les corrélations importantes et significatives entre le retrait transverse du bois de cœur et de l'aubier (0,87) indiquent que le retrait juvénile est un bon indicateur génétique de ce trait dans les arbres plus âgés.

---

* Corresponding author: phi.hong.hai@vbsg.slu.se or phi.hong.hai@fsiv.org.vn

1. INTRODUCTION

Plantation forestry is an attractive wood production option in the tropics because the rotation time is usually much shorter than in naturally regenerated stands. However, wood properties are likely to be affected because trees grown in plantations have a higher proportion of juvenile wood compared with trees from naturally regenerated slow-growing stands (Skaar, 1988). Rapid radial changes in juvenile wood properties occur within the stem. Since juvenile wood will be used increasingly in the future, there is a need for research on genetic variation in juvenile wood properties, their correlations with tree growth and their impact on end-use products (Zobel and Sprague, 1998).

Acacia auriculiformis, which occurs naturally in northern Australia, Papua New Guinea and West Papua, Indonesia, was selected as one of five priority species in the humid tropical lowlands. Its main attributes as a plantation species are rapid early growth, good wood quality for pulp, and wide range of solid wood products including furniture and framing in southeast Asia (Turnbull et al., 1997). Published studies of this species indicate there are significant differences in growth traits, stem form and wood density between provenances and between families within provenances (Hai et al., 2008a; 2008b; Khasa et al., 1995; Luangviriyasaeng and Pinyopusarerk, 2002). Improvement in growth, form, and wood basic density has been emphasized in the breeding of *A. auriculiformis* (Hai et al., 2008a; Turnbull et al., 1997). Efforts are underway to add wood properties such as strength and shrinkage, which have significant impacts on end-use products (Walker, 2006).

Shrinkage is one of the most important properties for dimensional stability of wood. Excessive shrinkage during drying causes warping (bow, cup, twist and spring), cracking and angular deformation in wood (Ormarsson et al., 1998; Skaar, 1988). Processed wood expands or shrinks in service according to ambient moisture levels, and excessive shrinkage can cause unacceptable defects in products such as flooring and furniture. Therefore, wood with low shrinkage is desirable in sawn-timber production and solid-wood products (Walker, 2006).

Wood is an anisotropic material: that is, its properties, including shrinkage rates, differ in three directions: tangentially, radially and longitudinally. In general, wood shrinks about twice as much tangentially as radially, and shrinks by a very small amount longitudinally (Cave, 1972; Zobel and Van Buijtenen, 1989). Juvenile wood tends to have less transverse (radial and tangential) shrinkage than mature wood because it has lower density (Bowyer et al., 2003). A high coefficient of anisotropy (the ratio between tangential and radial shrinkage) causes cup, cracking and angular deformation in wood during desorption (Chauhan and Aggarwal, 2004; Skaar, 1988). Longitudinal shrinkage and its variation over cross-sections of studs can cause distortions in terms of spring and/or bow. In Norway spruce (*Picea abies*), radial variation of the longitudinal shrinkage in the cross-section is assumed to be sufficient to predict spring and bow in studs (Johansson, 2002). Volumetric shrinkage provides an overall summary of the essential relationships between the shrinkage in various dimensions and the moisture content of wood (Bandara, 2006). Knowledge about genetic and within-tree variation for shrinkage traits and their relationships to other economically important traits are needed to include wood shrinkage as a selection criterion for dimensional stability in *A. auriculiformis* genetic improvement programs. To date, there is no information available on genetic variation in wood shrinkage traits in *A. auriculiformis*.

Nor Aini et al. (1997) reported broad-sense heritabilities of 0.38 and 0.44 for tangential and radial shrinkage of 5-year-old *A. crassicarpa* in a provenance-family trial. In *Eucalyptus grandis*, Bandara (Bandara, 2006) reported moderate narrow sense heritability estimates for partial shrinkage and high estimates for total tangential and radial shrinkage. Tangential shrinkage was under stronger genetic control than radial shrinkage. Sotelo Montes et al. (2007) also reported moderate to high heritability estimates for linear and volumetric shrinkages and lower heritabilities for shrinkage anisotropy in *Calycophyllum spruceanum*. Shrinkage traits showed weak positive genetic correlations with growth traits and basic wood density in *E. grandis* and *C. spruceanum* (Bandara, 2006; Sotelo Montes et al., 2007) even though standard errors of the estimates were high.

As part of a tree breeding program for *A. auriculiformis* in Vietnam, clonal tests were established at three contrasting sites: Ha Tay in the north, Quang Binh in north-central Vietnam and Binh Duong in the south. A previous study based on these trials showed clonal repeatabilities for growth traits and stem form traits in these tests were 0.21 to 0.56 at age 3–4 and increased with age (Hai et al., 2008b). Age-age genotypic correlations were strong for growth traits but ranged more widely (0.22 to 0.98) for stem-quality traits. Genotype by environment interaction in clonal growth performance was significant.

This paper presents results from studies of wood physical properties from the Binh Duong trial. The aim of the study was to investigate the possibility of genetically improving *A. auriculiformis* for solid wood production by studying the extent of genetic variation in wood shrinkage and genetic relationships between shrinkage traits, growth traits and wood density.

2. MATERIALS AND METHODS

The material for this study came from a test that included 120 clones from 61 families of *A. auriculiformis* established at Binh Duong in southern Vietnam in 2001. The clones were developed by coppicing the best three trees from each of the best 150 families selected for growth rate and stem straightness, in a 3-year-old progeny test of 192 open-pollinated families of *A. auriculiformis* in southern Vietnam (Hai et al., 2008b) at Binh Duong province, 11° 32′ N, 105° 56′ E, altitude 50 m a.s.l. The test environment was favorable for rapid growth of *A. auriculiformis*, with a mean annual rainfall of 2200 mm, a mean annual temperature of 26 °C and a free-draining sandy loam soil of moderate fertility. The test used a row-column design generated by the computer program CycDesign (Williams et al., 2002), with 8 replicates, each with 12 row and 10 column incomplete blocks. Each clone was represented by one two-ramet row plot in each replicate. The original spacing was 2 m between trees within rows and 4 m between rows.

Table I. Measured traits included in the analysis.

Abbreviation	Unit	Description
T_{hw}	%	Total tangential shrinkage of the heartwood
T_{sw}	%	Total tangential shrinkage of the sapwood
R_{hw}	%	Total radial shrinkage of the heartwood
R_{sw}	%	Total radial shrinkage of the sapwood
L_{hw}	%	Total longitudinal shrinkage of the heartwood
L_{sw}	%	Total longitudinal shrinkage of the sapwood
Tn_{hw}	%	Partial tangential shrinkage of the heartwood
Tn_{sw}	%	Partial tangential shrinkage of the sapwood
Rn_{hw}	%	Partial radial shrinkage of the heartwood
Rn_{sw}	%	Partial radial shrinkage of the sapwood
Ln_{hw}	%	Partial longitudinal shrinkage of the heartwood
Ln_{sw}	%	Partial longitudinal shrinkage of the sapwood
VoS	%	Total volumetric shrinkage
$VoSn$	%	Partial volumetric shrinkage
T/R		The coefficient of anisotropy (T/R ratio) for total shrinkage
Tn/Rn		The coefficient of anisotropy (Tn/Rn ratio) for partial shrinkage
HT	m	Total height
DBH	cm	Diameter at breast height
VOL	dm^3 $tree^{-1}$	Tree volume
DEN	$g\,cm^{-3}$	Basic density of pith-to-bark breast-height core

2.1. Measurements and sampling

All the traits under consideration in this study (Tab. I) were evaluated from a sample of 200 trees (5 ramets each of 40 clones). Forty clones are representatives of 31 families from Australia and Thailand. Clones and ramets selected for sampling were chosen at random and in total 8 replicates were represented. The measurements were carried out 5½ y after field planting. The mean height of the selected trees was 14 m and diameter at breast height (1.3 m) was 10.7 cm.

2.1.1. Wood shrinkage

The 200 selected trees were felled after the core samples were extracted. A billet 200 mm in length with its base at a height of 1.3 m was collected from each tree. The cut ends of the billets were immediately sealed with paraffin, stored in wet bags and transported directly to the Forest Science Institute of Vietnam wood laboratory. Sapwood and heartwood were visually delineated. Two defect-free standard specimens along the north-south cardinal direction from bark to bark (one in the dark heartwood and another in the light sapwood) were cut from each billet (Fig. 1) into rectangular prisms, 20 mm (tangential) × 20 mm (radial) × 30 mm (longitudinal).

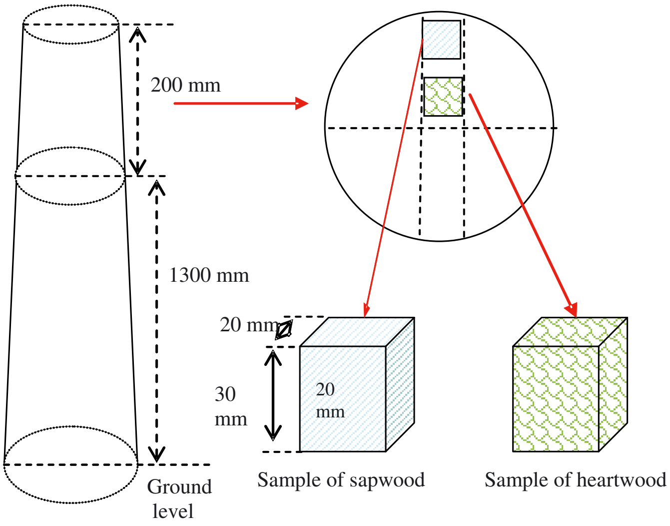

Figure 1. Sampling strategy of wood shrinkage and dimensions of the samples.

Sample preparation and measures of shrinkage in different directions followed ISO standard 4469-1981. Samples were soaked in distilled water for 72 h to ensure moisture content above the fiber saturation point. The dimensions were measured with a digital caliper to the nearest 0.001 mm at the mid-point on each axis of all three principal directions, which were marked for re-measurement. The specimens were subsequently placed in a conditioning chamber at 20 ± 2 °C and 65 ± 5% relative humidity (RH) for 45 d until they reached the equilibrium moisture content (EMC) at air-dry condition (EMC average = 12.68% ± 0.01%). Samples were then re-weighed, and dimensions were re-measured. The samples were oven dried at 103 °C for 8 d until a constant oven-dry weight was attained, and re-measured after samples had cooled to room temperature in a dry atmosphere maintained using silica gel in sealed containers.

Dimensional differences of samples were used to estimate partial (from green to 12% humidity) and total shrinkage (from green to oven-dry). Partial shrinkage was estimated in the tangential (Tn), radial (Rn), and longitudinal (Ln) dimensions and these values were used to calculate the partial coefficient of anisotropy (Tn/Rn) and partial volumetric shrinkage (VoSn). Total shrinkage (100 × [saturated – oven-dry dimension]/saturated dimension) was also estimated in the tangential (T), radial (R), and longitudinal (L) dimensions and used to calculate the total coefficient of anisotropy (T/R) and total volumetric shrinkage (VoS).

2.1.2. *Wood density*

A 5-mm bark-to-pith increment core was taken from each tree at 1.3 m and immediately sealed in an aluminium tube, and later frozen. Since it is difficult to recognize annual rings in the cores of this species, the cores were cut into two segments to estimate heartwood and sapwood density. The sapwood and heartwood were visually determined by colour, and area estimated. Density calculations used the water displacement method (Olesen, 1971). For each sample, the mass of water displaced by immersion ($W1$) and oven dry weight ($W2$) were measured. Density of each segment (DEN_{hw} and DEN_{sw}) was then calculated as: $DEN_{\mathrm{i}} = W2/W1$ (g cm^{-3}), and total core density (DEN) was then calculated as:

$$DEN = \frac{W2_{\mathrm{hw}} + W2_{\mathrm{sw}}}{W1_{\mathrm{hw}} + W1_{\mathrm{sw}}}\ (\mathrm{g\,cm^{-3}}) \tag{1}$$

where $W1_{\mathrm{hw}}$ and $W1_{\mathrm{sw}}$ are weights of water displaced by immersion of segments in heartwood and sapwood, respectively; and $W2_{\mathrm{hw}}$ and $W2_{\mathrm{sw}}$ are oven-dry weights of segments in heartwood and sapwood.

2.1.3. *Growth traits*

After the sampled trees were felled, total tree height (m) and diameter at breast height over bark (cm) were measured.

The conical stem volume was calculated using the following formula:

$$VOL = \frac{\pi}{12} \times HT \times DBH^2 \tag{2}$$

where HT is in dm, DBH is in dm and VOL is in dm^3 tree^{-1}.

2.2. Statistical analysis

The statistical analysis was conducted in two steps: (i) univariate analysis, where variance components for each trait were estimated; and (ii) bivariate analysis to estimate variances and covariances between pairs of characters. Row and column incomplete block effects within replicates were not modeled because the traits under consideration in this study were evaluated using a sub-sample of less than ¼ of the trees in the trial.

The following mixed linear model was used in the univariate analyses:

$$\mathbf{y} = \mathbf{Xb} + \mathbf{Zc} + \mathbf{e} \tag{3}$$

and the following bivariate model, which is an extension of model 3, was used in the two-trait analyses:

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{X}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_2 \end{bmatrix} \begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{Z}_1 & \mathbf{0} \\ \mathbf{0} & \mathbf{Z}_2 \end{bmatrix} \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \end{bmatrix} + \begin{bmatrix} \mathbf{e}_1 \\ \mathbf{e}_2 \end{bmatrix} \tag{4}$$

where $[\mathbf{y}_1]$ and $[\mathbf{y}_2]$ are observation vectors of the traits; $\mathbf{X}_1$ and $\mathbf{X}_2$ are design matrices for fixed replicate effects; $\mathbf{b}_1$ and $\mathbf{b}_2$ are vectors of fixed replicate effects; $\mathbf{Z}_1$ and $\mathbf{Z}_2$ are design matrices for random clone effects; $\mathbf{c}_1$ and $\mathbf{c}_2$ are vectors of random clone effects; $\mathbf{e}_1$ and $\mathbf{e}_2$ are vectors of random residuals, and may be summarized as

$$\mathbf{c}' = (\mathbf{c}'_1, \mathbf{c}'_1) \quad \text{and} \quad \mathbf{e}' = (\mathbf{e}'_1, \mathbf{e}'_1).$$

The random factors are assumed to be normally distributed with expected values of zero, leading to:

$$\mathbf{E}\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{X}_1\mathbf{b}_1 \\ \mathbf{X}_2\mathbf{b}_2 \end{bmatrix} \tag{5}$$

and with the variance-covariance matrix assumed to be

$$\mathrm{Var}\begin{bmatrix} \mathbf{c} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{G} \otimes \mathbf{I}_{\mathrm{c}} & \mathbf{0} \\ \mathbf{0} & \mathbf{R} \otimes \mathbf{I}_{\mathrm{n}} \end{bmatrix} \tag{6}$$

where $\mathbf{G}$ is the matrix with the clone variances and covariances, $\mathbf{R}$ is the matrix with the residual variances and covariances, and $\mathbf{I}_{\mathrm{c}}$ and $\mathbf{I}_{\mathrm{n}}$ are identity matrices for number of clones and trees, respectively. Finally, ⊗ symbolizes the Kronecker product.

Clonal variance (σ^2_{C}) and environmental variance (σ^2_{E}) for different traits were estimated using ASReml (Gilmour et al., 2006). The phenotypic (σ^2_{P}) variance was calculated as

$$\sigma^2_{\mathrm{P}} = \sigma^2_{\mathrm{C}} + \sigma^2_{\mathrm{E}}. \tag{7}$$

The estimated variance components were used to calculate the clonal repeatabilities for the traits under consideration. Clonal repeatability was calculated as:

$$H^2_{\mathrm{C}} = \frac{\sigma^2_{\mathrm{C}}}{\sigma^2_{\mathrm{C}} + \sigma^2_{\mathrm{E}}}. \tag{8}$$

Repeatability of clone means was calculated as:

$$H^2_{\overline{\mathrm{C}}} = \frac{\sigma^2_{\mathrm{C}}}{\sigma^2_{\mathrm{C}} + \dfrac{\sigma^2_{\mathrm{E}}}{r}} \tag{9}$$

where r is the number of ramets within clones. The genotypic coefficient of variation (CV_{G}), which expresses the genetic variance relative to the mean of the trait of interest, was calculated as:

$$CV_{\mathrm{G}} = \frac{100\sigma_{\mathrm{C}}}{\overline{x}}\ (\%) \tag{10}$$

where $\overline{x}$ is the phenotypic mean. The genotypic correlation (r_{G}) and phenotypic correlation (r_{P}) between traits or the same trait measured at different ages (sapwood and heartwood) were estimated as:

$$r_{\mathrm{G}} = \frac{\sigma_{\mathrm{C_1C_2}}}{\sigma_{\mathrm{C_1}}\sigma_{\mathrm{C_2}}} \tag{11}$$

$$r_{\mathrm{P}} = \frac{\sigma_{\mathrm{P_1P_2}}}{\sigma_{\mathrm{P_1}}\sigma_{\mathrm{P_2}}} \tag{12}$$

where $\sigma_{\mathrm{C_1C_2}}$ and $\sigma_{\mathrm{P_1P_2}}$ are the genotypic and phenotypic covariance between two traits, respectively. $\sigma_{\mathrm{C_1}}$, $\sigma_{\mathrm{C_2}}$ and $\sigma_{\mathrm{P_1}}$, $\sigma_{\mathrm{P_2}}$ are the genotypic and phenotypic standard deviations of trait 1 and trait 2. Standard errors of the estimates of the repeatabilities, genotypic and phenotypic correlations were calculated using a standard Taylor series approximation (Gilmour et al., 2006).

Table II. Mean values and standard errors for growth traits and shrinkage properties: genotypic coefficients of variation (CV_G), clonal repeatabilities (H^2_C), clonal mean repeatabilities ($H^2_{\bar{C}}$).

Trait	Mean	CV_G	H^2_C	$H^2_{\bar{C}}$
Total shrinkage				
T (%)	5.92	7.57	0.32 ± 0.08	0.70 ± 0.07
R (%)	3.23	7.53	0.38 ± 0.08	0.75 ± 0.06
L (%)	0.96	7.33	0.11 ± 0.07	0.37 ± 0.16
VoS (%)	11.45	7.16	0.40 ± 0.08	0.77 ± 0.06
T/R	1.85	8.02	0.18 ± 0.07	0.52 ± 0.12
Partial shrinkage				
Tn (%)	2.64	7.85	0.29 ± 0.08	0.67 ± 0.08
Rn (%)	1.64	5.45	0.16 ± 0.07	0.48 ± 0.13
Ln (%)	0.77	5.81	0.09 ± 0.06	0.33 ± 0.12
$VoS\,n$ (%)	4.98	5.82	0.32 ± 0.08	0.70 ± 0.08
Tn/Rn	1.82	6.73	0.17 ± 0.07	0.50 ± 0.13
Growth traits and Basic density				
DBH (cm)	10.73	6.72	0.29 ± 0.08	0.67 ± 0.08
HT (m)	14.15	3.36	0.20 ± 0.07	0.56 ± 0.11
VOL (dm^3)	43.67	16.77	0.33 ± 0.08	0.71 ± 0.07
DEN ($g\,cm^{-3}$)	0.54	4.72	0.47 ± 0.08	0.82 ± 0.05

Table III. Mean values and standard errors for shrinkage properties and basic wood density in heartwood and sapwood, respectively; genotypic coefficients of variation (CV_G), clonal repeatabilities (H^2_C), clonal mean repeatabilities ($H^2_{\bar{C}}$).

Trait	Mean	CV_G	H^2_C	$H^2_{\bar{C}}$
Total shrinkage (%) in heartwood and sapwood				
T_{hw}	4.86	7.34	0.14 ± 0.07	0.45 ± 0.14
T_{sw}	6.97	7.54	0.31 ± 0.08	0.70 ± 0.08
R_{hw}	2.97	8.78	0.15 ± 0.07	0.46 ± 0.14
R_{sw}	3.51	10.15	0.22 ± 0.07	0.59 ± 0.10
L_{hw}	0.96	4.84	0.04 ± 0.01	0.16 ± 0.07
L_{sw}	0.96	8.07	0.06 ± 0.03	0.26 ± 0.12
T/R_{hw}	1.7	1.09	0.08 ± 0.01	0.31 ± 0.02
T/R_{sw}	2.06	1.81	0.22 ± 0.02	0.58 ± 0.03
Partial shrinkage (%) in heartwood and sapwood				
Tn_{hw}	2.24	5.28	0.11 ± 0.07	0.39 ± 0.15
Tn_{sw}	3.04	9.53	0.29 ± 0.08	0.67 ± 0.08
Rn_{hw}	1.59	4.16	0.13 ± 0.07	0.43 ± 0.14
Rn_{sw}	1.7	6.43	0.21 ± 0.01	0.22 ± 0.08
Ln_{hw}	0.78	5.73	0.06 ± 0.03	0.24 ± 0.10
Ln_{sw}	0.77	5.97	0.03 ± 0.02	0.22 ± 0.09
T/Rn_{hw}	1.43	1.01	0.01 ± 0.001	0.06 ± 0.006
T/Rn_{sw}	1.84	1.04	0.13 ± 0.01	0.42 ± 0.03
Basic wood density in heartwood and sapwood ($g\,m^{-3}$)				
DEN_{hw}	0.52	5.12	0.50 ± 0.08	0.83 ± 0.04
DEN_{sw}	0.56	4.40	0.41 ± 0.08	0.77 ± 0.06

3. RESULTS

3.1. Mean values

The estimated mean values, coefficients of variation and repeatabilities of the studied traits are presented at the tree level in Table II and within-tree level in Table III. The mean values for total and partial shrinkage in the tangential direction were 5.92% and 2.64%, respectively (Tab. II). In the radial direction, the mean values were 3.23% for total shrinkage and 1.64% for partial shrinkage. Average longitudinal shrinkage was the lowest, 0.96% for total shrinkage and 0.77% for partial shrinkage. Shrinkage was much higher for volumetric than transverse dimensions: 11.45% and 4.98% for total and partial volumetric shrinkage, respectively. The total and partial shrinkages in transverse (tangential and radial) directions were significantly greater in the sapwood than in heartwood (Tab. III). For example, total tangential shrinkage in heartwood averaged 4.86%, compared to 6.97% for sapwood. In contrast, the longitudinal shrinkages of heartwood and sapwood were very similar. The mean ratio of tangential to radial shrinkage (coefficient of anisotropy) was around 1.85 (Tab. II) with clonal mean values ranging from 1.54 to 2.49 (data not shown). Sapwood tended to have a higher coefficient of anisotropy than heartwood (Tab. III). Mean wood density increased by 0.04 $g\,cm^{-3}$ from the heartwood to the sapwood.

3.2. Clonal repeatabilities and genotypic coefficients of variation

As reflected in the estimated clonal repeatabilities (H^2_C), clonal variance components were significant for transverse shrinkages, volumetric shrinkage and the coefficients of anisotropy, but not for longitudinal shrinkage. The genotypic coefficient of variation (CV_G) ranged from 5.45% to 8.02% for shrinkage traits (Tab. II), and were higher for total than for partial shrinkage. Furthermore, sapwood shrinkage trait CV_G values were consistently higher than the corresponding traits in the heartwood (Tab. III). For both total and partial shrinkage, the estimates of H^2_C were 0.32 to 0.40 for volumetric shrinkage, 0.16 to 0.38 for transverse shrinkage and 0.17 to 0.18 for the coefficients of anisotropy (Tab. II). Estimates of H^2_C were low for longitudinal shrinkages (0.03 to 0.11). Estimated clonal repeatabilities of the sapwood shrinkage traits showed generally higher CV_G values than corresponding estimates of the heartwood (Tab. III).

3.3. Genetic correlations

There were no significant genetic relationships detected between the growth traits (DBH, HT and VOL) and the total shrinkage traits (T, R, L and VoS) as seen from the estimated genotypic correlations (Tab. IV). The correlations were negative and small, indicating a weak tendency of fast-growing clones to have minor wood shrinkage. The same trend was

Table IV. Genotypic correlations (significant correlations in bold, $p \leq 0.05$) and standard errors of correlations (within parenthesis) among total shrinkage and between total shrinkage and growth traits and density.

Trait	*T*	*R*	*L*	*T/R*	*VoS*
DBH	–0.18	–0.14	–0.08	–0.02	–0.13
	(0.23)	(0.22)	(0.33)	(0.28)	(0.22)
HT	–0.04	–0.01	–0.13	–0.45	–0.01
	(0.26)	(0.25)	(0.36)	(0.29)	(0.25)
VOL	–0.09	–0.10	–0.11	–0.08	–0.11
	(0.23)	(0.22)	(0.32)	(0.27)	(0.22)
DEN	0.25	0.22	0.55	0.21	0.24
	(0.20)	(0.20)	(0.28)	(0.24)	(0.20)
T		**0.99**	–0.10	–0.10	**0.99**
		(0.04)	(0.32)	(0.27)	**(0.01)**
R			–0.53	–0.10	**0.99**
			(0.27)	(0.26)	**(0.01)**
L				**0.88**	–0.30
				(0.38)	(0.29)
T/R					0.01
					(0.08)

Table V. Genotypic correlations (significant correlations in bold, $p \leqslant 0.05$) and standard errors of correlations (within parenthesis) among partial shrinkage and between partial shrinkage and growth traits and density.

Trait	*Tn*	*Rn*	*Ln*	*Tn/Rn*	*VoSn*
DBH	–0.20	–0.11	–0.12	–0.06	–0.18
	(0.24)	(0.29)	(0.35)	(0.28)	(0.23)
HT	0.08	0.51	0.26	–0.4	0.21
	(0.27)	(0.30)	(0.40)	(0.30)	(0.26)
VOL	–0.13	–0.05	–0.08	–0.04	–0.10
	(0.23)	(0.28)	(0.34)	(0.28)	(0.24)
DEN	0.12	0.01	0.16	0.21	0.09
	(0.22)	(0.26)	(0.31)	(0.25)	(0.21)
Tn		**0.93**	–0.15	–0.26	**0.99**
		(0.16)	(0.35)	(0.30)	**(0.01)**
Rn			**–0.93**	**–0.71**	**0.99**
			(0.45)	**(0.19)**	**(0.01)**
Ln				**0.87**	–0.29
				(0.40)	(0.29)
Tn/Rn					–0.40
					(0.26)

Table VI. Relationships among genetic correlations (r_G: mean and standard error) for sampled dimensions and between total and partial shrinkage.

Correlations	r_G
Total shrinkage vs. partial shrinkage	
T vs. Tn	0.94 (0.06)
R vs. Rn	0.82 (0.16)
L vs. Ln	0.57 (0.23)
T/R vs. Tn/Rn	0.99 (0.00)
VoS vs. $VoSn$	0.94 (0.07)
Heartwood shrinkage vs. sapwood shrinkage	
T_{hw} vs. T_{sw}	0.87 (0.20)
R_{hw} vs. R_{sw}	0.95 (0.26)
L_{hw} vs. L_{sw}	0.91 (0.21)
Tn_{hw} vs. Tn_{sw}	0.70 (0.32)
Rn_{hw} vs. Rn_{sw}	0.78 (0.56)
Ln_{hw} vs. Ln_{sw}	0.89 (0.30)
T_{hw}/R_{hw} vs. T_{sw}/R_{sw}	0.99 (0.00)
Tn_{hw}/Rn_{hw} vs. Tn_{sw}/Rn_{sw}	0.71 (0.01)

also evident for the relationships between the partial shrinkage and *DBH* and *VOL* (Tab. V). Nevertheless, *HT* correlated positively and unfavorably with partial shrinkage. All total and partial shrinkage traits showed positive correlations with basic density (from 0.01 to 0.55), but no significant correlations with growth traits.

All total shrinkage traits had very strong positive correlations with partial shrinkage traits in corresponding directions (Tab. VI). Similarly, all heartwood shrinkage traits were strongly positively correlated with sapwood shrinkage in the same direction (Tab. VI).

4. DISCUSSION

This study's primary focus was on traits influencing dimensional stability of wood: shrinkage in different directions, volumetric shrinkage and the coefficient of anisotropy. Since the trees used in this study were young, they consisted of juvenile wood. The results showed substantial genotypic variation between clones for growth, wood density and wood transverse shrinkage and suggest that deployment of *A. auriculiformis* clones can be achieved in improvement of wood properties for sawn-timber production.

4.1. Mean values of the shrinkage properties

Our mean values for transverse shrinkage (Tab. II) agree with those of Nor Aini et al. (1997) who reported tangential shrinkage ranged from 4.1% to 4.8%, and radial shrinkage ranged from 2.1% to 3.0% in an 8-year-old provenance trial of *A. auriculiformis* in Malaysia. These values were greater than the 2.6% for tangential shrinkage and 1.3% for radial shrinkage observed in trees from a 13-year-old plantation in Thailand (Chomchran et al., 1986). Similarly, our volumetric shrinkage also was higher than the value of 8.0% that was found in a study by Aggarwal et al. (2002) in 20-year-old *A. auriculiformis*. However, direct comparison is not appropriate because final moisture content varied from study to study. Wood samples were taken at different heights or at different distances from the pith to the bark, and the trees were of different ages and had grown at different sites.

The coefficient of anisotropy provides important information on the dimensional stability of wood. A low ratio reflects dimensional stability (Skaar, 1988). In the present study, this ratio was 1.85 and 1.82 for total and partial shrinkage, respectively (Tab. II). These calculated ratios were larger than the ratio (1.14–1.66) reported for *Tectona grandis* (Dinwoodie, 2000), *E. globulus* (Yang, 2003), *E. citriodora* (Bao et al., 2001), *Quercus robur* and *Q. rubra* (Nepveu, 1984). The high transverse anisotropy also indicates that juvenile wood of *A. auriculiformis* may display instability and high distortion during drying, leading especially to the occurrence of cup and angular deformation in end products and the opening of large radial cracks (Brunetti et al., 2001). The large transverse anisotropy may be due to a combination of factors, including the restraining effect of ray cells, and differences in cell wall thickness and lignin content between the radial and tangential faces of fibres (Skaar, 1988; Zobel and Sprague, 1998).

Little radial variation with respect to longitudinal shrinkage between the samples from heartwood and sapwood was found in this study, consistent with a finding in *A. mangium* (Shams et al., 2005). The pattern of radial variation of shrinkage is important, especially in young trees with large proportions of juvenile wood (Shupe et al., 1995). Modest radial variation in longitudinal shrinkage is enough to make sawn wood products unstable and cause warping and twisting in after drying (Johansson, 2002). A comparison made in our study between heartwood and sapwood (Tab. III) showed that there is no difference between longitudinal shrinkage in these two types of wood. The result indicates that there will be only minor problems with spring and bow in *A. auriculiformis*. In contrast with the lack of radial variation in longitudinal shrinkage, there was a general pattern of increasing transverse shrinkage and coefficient of anisotropy from heartwood to sapwood (Tab. III). Shrinkage increased with increasing distance from the pith to bark, corresponding to an increase in basic density from pith to bark (Tab. III) and reported previously in *A. auriculiformis* (Hai et al., 2008c). The increasing trends of shrinkage and coefficient of anisotropy from the pith to bark are in accordance with volumetric shrinkage in *A. auriculiformis* (Aggarwal et al., 2002), transverse shrinkage in a review of *Eucalyptus* species (Raymond, 2002), and transverse and volumetric shrinkage in yellow poplar (Koubaa et al., 1998; Shupe et al., 1995), *Q. petraea* and *Q. robur* (Zhang et al., 1994).

4.2. Clonal repeatabilities and genotypic coefficients of variation

The moderate to high repeatability estimates of the transverse shrinkage traits in our study (Tab. II) are consistent with previous estimates available from the literature. In *Acacia* species, Nor Aini et al. (1997) reported that the broad-sense heritabilities were 0.38 and 0.44 for tangential and radial shrinkage of 5-year-old *A. crassicarpa* in a progeny trial. Moderate to high heritability estimates for tangential and radial shrinkage have also been demonstrated in other hardwood species, such as *E. grandis* (Bandara, 2006), *E. dunnii* (Henson et al., 2004), hybrid poplar (Koubaa et al., 1998) and *Carycophyllum spruceanum* (Sotelo Montes et al., 2007). The H_C^2 of tangential and radial shrinkage increased from 0.11 in heartwood to 0.31 in sapwood, thus increasing with age. Low (non-significant) H_C^2 estimates of longitudinal shrinkage in heartwood and sapwood suggest that there is little or no genetic control of radial differences. The low repeatability of longitudinal shrinkage is due at least in part to the low values in longitudinal shrinkage in both heartwood and sapwood, making this trait difficult to assess in small wood blocks.

The significant genotypic variation in wood shrinkage traits (except for longitudinal shrinkage) in our study is also consistent with results from studies in hybrid poplar clones (Koubaa et al., 1998; Pliura et al., 2005; Sotelo Montes et al., 2007), families of *E. dunnii* (Bandara, 2006; Henson et al., 2004) and *E. grandis* (Bandara, 2006). In this study, most of the total and partial shrinkages had higher CV_G values than height, diameter and density. High repeatabilities and CV_G indicate that selection would be effective in improvement of shrinkage traits of *A. auriculiformis* clones.

Improvements to reduce shrinkage anisotropy will become more important when the use of drying technology becomes more popular and commonly adopted (Walker, 2006) in Vietnam. Judging from CV_G in our study, tangential shrinkage showed slightly more variation than radial shrinkage, while partial shrinkage showed relatively more variation than total shrinkage (Tab. II). A similar result for juvenile wood of the same species was reported by Aggarwal et al. (2002) and Chomcharn et al. (1986).

4.3. Genotypic correlations

Several studies have shown that growth rate and some properties of wood, like the basic density and volumetric shrinkage, are not strongly correlated at the phenotypic and/or genetic levels in *A. auriculiformis* (Hai et al., 2008c; Khasa et al., 1995; Kumar et al., 1987). In other hardwood species, such as *Eucalyptus* species, *Q. petrea*, *Q. rubra*, *Petersianthus macrocarpa* and *C. spruceanum*, positive correlations between shrinkage parameters and basic density have been reported (Chafe, 1994; Nepveu, 1984; Sotelo Montes et al., 2007).

The small sample size in our study (only 40 clones) causes a large standard error to the genetic correlations and the correlations must therefore be interpreted with caution. Growth rate had a slightly negative correlation with wood density, but this was not significant (data not shown). This is consistent with the underlying non-significant negative relationship between growth rate and wood density in a previous study of a progeny trial of *A. auriculiformis* in northern Vietnam (Hai et al., 2008c). Similarly, growth rate had weak and non-significant negative correlations with wood shrinkage, except for the relationships between partial shrinkage and height.

In our study, denser wood tended to have slightly greater transverse shrinkage and T/R ratio based on the positive, but non-significant, phenotypic (data not shown) and genotypic correlations (Tabs. IV and V) and the comparison between heartwood and sapwood traits for density and the T/R ratio (Tab. III). Sotelo Montes et al. (2007) also reported positive phenotypic and genotypic correlations between density and the T/R ratio for *C. spruceanum*. Similar results were obtained in other hardwood species, such as *Terminali superba* and *Tectona grandis* (Hock and Mariaux, 1984). Increasing wood density in selection and breeding of *A. auriculiformis*, therefore, should be carefully considered to avoid unstable wood.

Strong significant correlations between partial and total shrinkage also suggested that latter would be a good indirect measure of the former (which is the target trait). This will reduce the cost, time and technology required to test shrinkage, avoiding the need to dry wood under controlled temperature and humidity conditions. Furthermore, the similar strong correlations between heartwood shrinkages and sapwood shrinkages also showed that heartwood (younger) traits are good genetic indicators of the sapwood (older) traits, and that there will be more gain per unit time with selection at an earlier age (Zobel and Sprague, 1998).

4.4. Implications for breeding

The relationships reported here were based on juvenile wood. In Vietnam, a typical rotation of most *Acacia* species is about 5–7 y for pulpwood and 7–15 y (depending on location) for sawn-timber production, so the sawn timber industry in Vietnam is largely based on juvenile wood. The size of the larger trees studied in the Binh Duong clonal trial was quite close to typical final harvest size, since a DBH of 15 cm can be accepted for sawn timber by some sawmills. Furthermore, the piece sizes used in most Vietnamese furniture factories are less than 1200 mm long, so bow and spring are not major problems for most processors, since longer sawn boards will be cut into short sections, reducing or eliminating these defects.

Mean values of the shrinkage properties suggest that improvement for the total transverse shrinkage and coefficient of anisotropy would be more important than for other shrinkages in *A. auriculiformis*. Substantial genotypic variation between clones and moderate to high clonal repeatability estimates for these traits, moreover, affirmed that considerable genetic improvement can be achieved in wood properties important for sawn-timber production in the population of clones sampled in this study.

The demand for uniform raw materials is likely to increase in the future (Walker, 2006). Non-significant correlations between growth and shrinkage suggest that selection of individuals with rapid growth and low shrinkage values in breeding and deployment programs would be a feasible way to improve the uniformity of *A. auriculiformis* wood. Examination of plots of BLUP (Best Linear Unbiased Prediction) values of volume and the coefficients of anisotropy for the studied clones (data not presented) demonstrated the possibility of selecting fast-growing clones with a low coefficient of anisotropy.

A cheaper and more rapid means of measuring shrinkage is needed than wood blocks used for this paper. There are some obvious alternatives. Firstly, near infrared diffuse reflectance spectroscopy (NIRS) is a highly promising method that could be adapted for rapid measurements on wood (Baillères et al., 2002). Secondly, an optical microscope equipped with reflected light, a standard objective, a water immersion objective of same magnification and a digital camera connected to a computer would be also a good method to study free shrinkage at the tissue level and radial variation of shrinkage (Perré and Huber, 2007).

A selection index based on genetic parameters and economic weights for e.g. height, diameter, density, shrinkage, combined with a threshold value for other traits like forking and stem straightness could also deliver significant benefits in breeding for improved growth, stem straightness, shrinkage and wood density. Detailed bio-economic modeling (Ivkovic et al., 2006) of acacia growing and processing systems in Vietnam has not yet been undertaken. *A. auriculiformis* has sufficiently high basic density for the Vietnamese furniture industry, so there is no strong requirement to increase density. The industry successfully uses large volumes of wood from clones of the *A. mangium* × *A. auriculiformis* hybrid, which has lower density than *A. auriculiformis* (Kha, 2001). Reduced shrinkage and anisotropy will increase the recovery of useable wood for the furniture industry, so these may be more important traits than density in breeding and clonal selection for *A. auriculiformis* in Vietnam.

5. CONCLUSIONS

We assessed genetic variation in wood transverse shrinkage and coefficients of anisotropy in fast-growing clones of *A. auriculiformis* at 5¹/₂ y. There was greater variation in total shrinkage than in partial shrinkage dimensions. The total and partial transverse shrinkage were significantly greater in the sapwood than in heartwood. These results, together with the moderate clonal repeatability levels and moderate to high genotypic variation show that there is potential to improve and select for lower shrinkage. Genetic correlations indicate that density and shrinkage would not be adversely affected if faster-growing clones were selected. The results presented in this study were based on trees that came from a single clonal test, so it would be important to test whether site conditions affect the correlations among traits.

Acknowledgements: The clone trial used in this study was established by the Research Centre for Forest Tree Improvement in collaboration with CSIRO Forestry and Forest Products and with support from the ACIAR-funded Domestication of Australian Trees Project. The authors acknowledge staff in the Research Centre for Forest Tree Improvement in Hanoi and the Centre of South Eastern Forest Science and Production who worked on establishment, maintenance of the trials, data collection and wood sampling. The authors also would like to thank Dr. Kevin Harding for his comments and staff in Forest and Plant Resource Division of Forest Science Institute of Vietnam for support in the use of wood-testing equipment and preparation of the samples. This study was funded by a SIDA/SAREC project.

REFERENCES

Aggarwal P.K., Chauhan S.S., and Karmarkar A., 2002. Variation in growth strain, volumetric shrinkage and modulus of elasticity and their inter-relationship in *Acacia auriculiformis*. J. Trop. For. Sci. 8: 135–142.

Baillères H., Davrieux F., and Ham-Pichavant F., 2002. Near infrared analysis as a tool for rapid screening of some major wood characteristics in a *Eucalyptus* breeding program. Ann. For. Sci. 59: 479–490.

Bandara K.M.A., 2006. Genetic improvement of solid wood product value of subtropical eucalypts: a case study of *Eucalyptus grandis* and *E. dunnii*, Ph.D. thesis at the Australian national university, 215 p.

Bao F.C., Jiang Z.H., Lu X.X., Luo X.Q., and Zhang S.Y., 2001. Differences in wood properties between juvenile and mature wood in 10 species grown in China. Wood Sci. Technol. 35: 362–375.

Bowyer J.L., Shmulsky R., and Haygreen J.G., 2003. Forest products and wood science: an introduction, Iowa state university press, Ames, Iowa, 558 p.

Brunetti M., De Capua E.L., Macchioni N., and Monachello S., 2001. Natural durability, physical and mechanical properties of Atlas cedar (*Ceddrus atlantica* Manetti) wood from Southern Italy. Ann. For. Sci. 58: 607–613.

Cave I.D., 1972. A Theory of the Shrinkage of Wood. Wood Sci. Technol. 6: 284–292.

Chafe S.C., 1994. Relationship between shrinkage and specific gravity in the wood of *Eucalyptus*. Australia forestry 57: 59–61.

Chauhan S.S. and Aggarwal P., 2004. Effect of moisture sorption state on transverse dimensional changes in wood. Holz Roh-Werkst. 62: 50–55.

Chomchran A., Visuthidepakul S., and Hortrakul P., 1986. Wood properties and potential uses of 14 fast-growing tree species, Division of forest product research, Royal forest department, Thailand, 22 p.

Dinwoodie J.M., 2000. Timber: Its nature and behaviour, Taylor and Francis, London, 272 p.

Gilmour A.R., Gogel B.J., Cullis B.R., Welham S.J., and Thompson R., 2006. ASREML user guide, Release 2.0. VSN international Ltd, Hemel Hempstead, UK, 342 p.

Hai P.H., Harwood C., Kha L.D., Pinyopusarerk K., and Thinh H.H., 2008a. Genetic gain from breeding *Acacia auriculiformis* in Vietnam. J. Trop. For. Sci. 20: 313–327.

Hai P.H., Jansson G., Harwood C., Hannrup B., and Thinh H.H., 2008b. Genetic variation in growth, stem straightness and branch thickness in clonal trials of *Acacia auriculiformis* at three contrasting sites in Vietnam. For. Ecol. Manage. 255: 156–167.

Hai P.H., Jansson G., Harwood C., Hannrup B., Thinh H.H., and Pinyopusarerk K., 2008c. Genetic variation in wood basic density and knot index and their relationship with growth traits for *Acacia auriculiformis* A. Cunn ex Benth in Northern Vietnam. N. Z. J. For. Sci. 38: 176–192.

Henson M., Boyton S., Davies M., Joe B., Kangane B., Murphy T., Palmer G., and Vanclay J., 2004. Genetic parameters of wood properties in a 9 years old *Eucalyptus dunnii* progeny trial in NSW, Australia. In: Borralho N.M.G., Pereira J.S., Marques J., Coutinho J., Madeira M., and Tome R.M. (Eds.), *Eucalyptus* in a changing world, IUFRO, Portugal, 83 p.

Hock R. and Mariaux A., 1984. Vitesse de croissance et retrait du bois : relation entre la largeur des cernes d'accroissement et le retrait au séchage dans quelques arres tropicaux. Rev. Bois. For. Trop. 203: 79–90.

Ivkovic M., Wu H., McRae T., and Powell M., 2006. Developing breeding objectives for radiata pine structural wood production. I. Bioeconomic model and economic weights. Can. J. For. Res. 36: 2920–2931.

Johansson M., 2002. Moisture-induced distortion in Norway spruce timbe – experiments and models, Ph.D. thesis at Chalmens university of Technology, Gothenburg, Sweden.

Kha L.D., 2001. Studies on natural hybrids of *Acacia mangium* and *A. auriculiformis* in Vietnam, Agriculture Publishing House, Ha Noi, 171 p.

Khasa P.D., Li P., Vallee G., Magnussen S., and Bousquet J., 1995. Early evaluation of *Racosperma auriculiforme* and *R. mangium* provenance trials on four sites in Zaire. For. Ecol. Manage. 78: 99–113.

Koubaa A., Hernandez R.E., and Beaudoin M., 1998. Shrinkage of fast-growing hybrid poplar clones. For. Prod. J. 48: 82–87.

Kumar P., Anathanarayana A.K., and Sharma S.N., 1987. Physical and mechanical properties of *Acacia auriculiformis* from Karnataka. Indian Forester 113: 567–573.

Luangviriyasaeng V. and Pinyopusarerk K., 2002. Genetic variation in second-generation progeny trial of *Acacia auriculiformis* in Thailand. J. Trop. For. Sci. 14: 131–144.

Nepveu G., 1984. Genetic control of wood density and shrinkage in three oak species (*Quercus petraea, Quercus robur* and *Quercus rubra*). Silv. Genet. 33: 110–115.

Nor Aini A.S. et al., 1997. Selected wood properties of *Acacia auriculiformis* and *A. crassicarpa* provenances in Malaysia. In: Turnbull J.W., Crompton H.R., and Pinyopusarerk K. (Eds.), Recent developments in *Acacia* planting, Australian Centre for Internatinal Agricultural Research, Ha Noi, Vietnam, pp. 155–160.

Olesen P.O., 1971. The water displacement method. For. Tree Improv. 3: 1–23.

Ormarsson S., Dahlblom O., and Petersson H., 1998. A numerial study of the shape stability of sawn timber subjected to moisture variation. Wood Sci. Technol. 32: 325–334.

Perré P. and Huber F., 2007. Measurement of free shrinkage at the tissue level using an optical microscope with an immersion objective: results obtained for Douglas fir (*Pseudotsuga menziesii*) and spruce (*Picea abies*). Ann. For. Sci. 64: 255–265.

Pliura A., Yu Q., Zhang S.Y., MacKay J., Périnet P., and Bousquet J., 2005. Variation in wood density and shrinkage and their relationship to growth of selected young poplar hybrid crosses. For. Sci. 51: 472–482.

Raymond C.A., 2002. Genetics of *Eucalyptus* wood properties. Ann. For. Sci. 59: 525–531.

Shams M.I., Chowdhury M.Q., and Alam M., 2005. Effects of age and height variation on physical properties of mangium (*Acacia mangium* Willd.) wood. Australian Forestry 68: 17–19.

Shupe T.F., Choong E.T., and Gibson M.D., 1995. Differences in moisture content and shrinkage between outerwood, middlewood, and corewood of two yellow-poplar trees. For. Prod. J. 45: 85–90.

Skaar C., 1988. Wood water relations, Springer-Verlag, New York, 283 p.

Sotelo Montes C., Beaulieu J., and Hernandez R.E., 2007. Genetic variation in wood shrinkage and its correlations with tre growth and wood density of *Calycophyllum spruceanum* at an early age in the Peruvian Amazon. Can. J. For. Res. 37: 966–976.

Turnbull J.W., Midgley S.J., and Cossalter C., 1997. Tropical Acacias planted in Asia: an Overview Recent Developments in Acacias planting. In: Turnbull J.W., Crompton H.R., and Pinyopuserak K. (Eds.), Recent developments in *Acacia* planting, ACIAR Publishing, Ha Noi, Vietnam, pp. 14–18.

Walker J.C.F., 2006. Primary wood processing: principles and practice, Springer, Dordrecht, The Netherlands, 603 p.

Williams E.R., Matheson A.C., and Harwood C.E., 2002. Experimental design and analysis for tree improvement, CSIRO publishing, 220 p.

Yang J.L., 2003. Interrelationships between shrinkage properties, microfibril angle, and cellulose crystallits width in 10-year-old *Eucalyptus globules*. For. Prod. J. 33: 47–61.

Zhang S.Y., Nepveu G., and Eyono Owoundi R., 1994. Intratree and intertree variation in selected wood quality characteristics of European oak (*Quercus petraea* and *Quercus robur*). Can. J. For. Res. 24: 1818–1823.

Zobel B. and Van Buijtenen J.P., 1989. Wood variation: its causes and control, Springer, Berlin, Heidelberg, New York, 363 p.

Zobel B.J. and Sprague J.R., 1998. Juvenile wood in forest trees, Springer-Verlag, Telos, Berlin, 300 p.