PHYSICAL AND MECHANICAL PROPERTIES OF EIGHT FAST-GROWING PLANTATION SPECIES IN COSTA RICA

R Moya* & F Muñoz

Escuela de Ingeniería Forestal, Instituto Tecnológico de Costa Rica, PO Box 159-7050, Cartago, Costa Rica

Received May 2009

MOYA R & MUÑOZ F. 2010. Physical and mechanical properties of eight fast-growing plantation species in Costa Rica. Wood properties of *Acacia mangium* (*Am*), *Alnus acuminata* (*Aa*), *Bombacopsis quinata* (*Bq*), *Cupressus lusitanica* (*Cl*), *Swietenia macrophylla* (*Sm*), *Terminalia amazonia* (*Ta*), *Terminalia oblonga* (*To*) and *Vochysia guatemalensis* (*Vg*) planted in Costa Rica were determined. Heartwood (HWC), bark (BP) and pith (PP) proportions, specific gravity (SG), green moisture content (GMC), green density (GD) and mechanical properties were evaluated. Heartwood percentage was lower in *Aa*, *Bq*, *Ta*, *To* and *Vg* and highest in *Cl* and *Am*. Lower PP was measured in *Cl*, *Sm* and *Bq*. The lowest SG values were found in *Bq*, *Vg* and *Aa* while the highest, in *To*, *Am* and *Cl*. The lowest GMCs were measured in *Sm*, *Ta* and *To* while the highest, in *Bq* and *Vg*. Highest GD values were detected in *Am* and *Cl*, and the lowest, in *Aa*. Heartwood, SG, GMC and GD varied with tree height in all species. *Swietenia macrophylla* consistently yielded high values for most mechanical tests. *Terminalia oblonga* also had high values for mechanical properties. The lowest mechanical properties were recorded in *Vg* and *Bq*.

Keywords: Tropical species, Central America, wood variation

MOYA R & MUÑOZ F. 2010. Ciri-ciri fizikal dan mekanik lapan spesies hutan ladang yang tumbuh cepat di Costa Rica. Ciri-ciri kayu pokok *Acacia mangium* (*Am*), *Alnus acuminate* (*Aa*), *Bombacopsis quinata* (*Bq*), *Cupressus lusitanica* (*Cl*), *Swietenia macrophylla* (*Sm*), *Terminalia amazonia* (*Ta*), *Terminalia oblonga* (*To*) dan *Vochysia guatemalensis* (*Vg*) yang ditanam di Costa Rica dinilai. Kayu teras (HWC), perkadaran kulit pokok (BP) dan perkadaran empulur (PP), graviti tentu, kandungan lembapan basah, ketumpatan basah dan ciri-ciri mekanik kayu tersebut dinilai. Peratusan HWC adalah rendah dalam *Aa, Bq, Ta, To* dan *Vg* tetapi tinggi dalam *Cl* dan *Am*. Nilai PP adalah rendah dalam *Cl, Sm* dan *Bq*. Nilai SG paling rendah dicerap dalam *Bq, Vg* dan *Aa* manakala nilainya paling tinggi dalam *To, Am* dan *Cl*. Nilai GMC paling rendah dalam *Sm, Ta* dan *To* tetapi paling tinggi dalam *Bq* dan *Vg*. Nilai GD paling tinggi dalam *Am* dan *Cl* tetapi paling rendah dalam *Aa*. Kayu teras, SG, GMC dan GD berbeza dengan ketinggian pokok dalam semua spesies. *Swietenia macrophylla* secara konsistennya menunjukkan nilai yang tinggi untuk kebanyakan ujian mekanik. *Terminalia oblonga* juga menunjukkan nilai yang tinggi. Nilai ciri mekanik paling rendah dalam *Vg* dan *Bq*.

INTRODUCTION

Costa Rica and other countries in Central America possess a great stock of hardwood timber from natural as well as from plantation forests (Moya 2004). Native and exotic species have acquired commercial importance in reforestation projects based on the limited knowledge of their genetic, reproductive and forest plantation management. By the year 2006, 50 000 ha of these species were enumerated as being from forest plantations for production purposes, limiting the establishment of a sustainable wood trade market (Barrantes & Castro 2007).

Relatively fast-growing species (with rotation periods of less than 30 years), such as *Terminalia amazonia*, *Terminalia oblonga*, *Vochysia guatemalensis*, *Bombacopsis quinata*, *Alnus acuminata* and *Swietenia macrophylla* (native species), and *Tectona grandis*, *Cupressus lusitanica*, *Acacia mangium* and *Gmelina arborea* (exotic species) have shown excellent results in plantation forestry in Costa Rica (Murillo *et al.* 2001, Pérez & Kanninen 2001, Moya 2004, Petit & Montagnini 2004). Native species are an encouraging factor currently promoting reforestation because they can be planted on abandoned lands for economic activity, promote agroforestry and help in carbon sequestration (González & Fisher 1994, Petit & Montagnini 2004).

Many references can be found for *T. grandis* and *G. arborea* in Costa Rica. These species were

*E-mail: rmoya@itcr.ac.cr

studied for various wood properties (Pérez & Kanninen 2003, 2005, Moya *et al.* 2008, Moya & Tomazello 2008). However, few studies on the properties of other plantation species have been found. When wood properties were determined, they were limited to a reduced number of characteristics. For example, Butterfield *et al.* (1993) carried out a study on the radial variation of the basic density, fibre length and vessel area from pith to bark in *Hyeronima alchorneoides* and *V. guatemalensis*, comparing trees grown in natural conditions with those grown in plantations. González and Fisher (1998) studied the specific gravity, fibre length, vessel density and vessel radial diameter from pith to bark in natural forests of *V. guatemalensis* in Costa Rica, while Moya (2000) evaluated the sawmilling process of 6-year-old *T. amazonia* trees from fast-growing plantations in Costa Rica.

The choice of plantation species for a particular end-use requires consideration of many factors. In general, the choice may depend upon one or a combination of wood properties. Although the specific gravity (SG) of the wood is the most commonly studied wood property—because it is a good indicator of many working properties—there are other wood properties not related to the SG that can affect end-use requirements (Zobel & Van Buijtenen 1989).

The remarkable difference in wood properties between species means that information about the quality and utilisation potential of promising plantation species must be taken into consideration. There is a great number of wood properties that have some influence on wood products or wood processing. However, it is necessary to first identify the main characteristics that determine the quality of the wood products (Laurila 1995).

Considering the increasing demand for new species from fast-growth plantations as alternative timbers for tropical wood, a study was conducted to compare the different wood properties of eight species growing under fast-growth conditions in Costa Rica. Thus, the aim of the present study was to evaluate the physical and mechanical properties of *A. mangium*, *A. acuminata*, *B. quinata*, *C. lusitanica*, *S. macrophylla*, *T. amazonia*, *T. oblonga* and *V. guatemalensis*.

MATERIALS AND METHODS

Site, plantation description and tree sampling

Eight different pure plantations located in several parts of Costa Rica were studied. The initial planting density was 1111 trees ha^{-1} (3 × 3 m spacing). At the time of evaluation, the age range was 9–18 years old and the density was 338–556 trees ha^{-1} (Table 1). A total of nine trees per species were randomly selected for harvesting, including suppressed, intermediate and dominant trees, in accordance with the methodology developed by Moya *et al.* (2002). Selected trees with straight trunks, normal branching and no disease or pest symptoms were felled. From each selected tree, two 1.3 m logs were obtained—one from the tree base to diameter at breast height (dbh) and another from dbh to 25% height. (Figure 1). From these logs, a cross-sectional sample, 3 cm thick, was taken at 1.3 m height (dbh). Stem

Table 1 Dasometric information for the plantations sampled

Species	Age (years)	Density (trees ha^{-1})	Total height (m)	Dbh (cm)
Alnus acuminata	9	556	20.7	20.5
Acacia mangium	9	338	19.0	36.7
Bombacopsis quinata	10	480	16.7	21.5
Cupressus lusitanica	10	525	20.7	18.5
Swietenia macrophylla	14	452	21.4	22.6
Terminalia amazonia	13	475	21.85	25.2
Terminalia oblonga	18	408	19.2	28.0
Vochysia guatemalensis	8	515	22.7	18.5

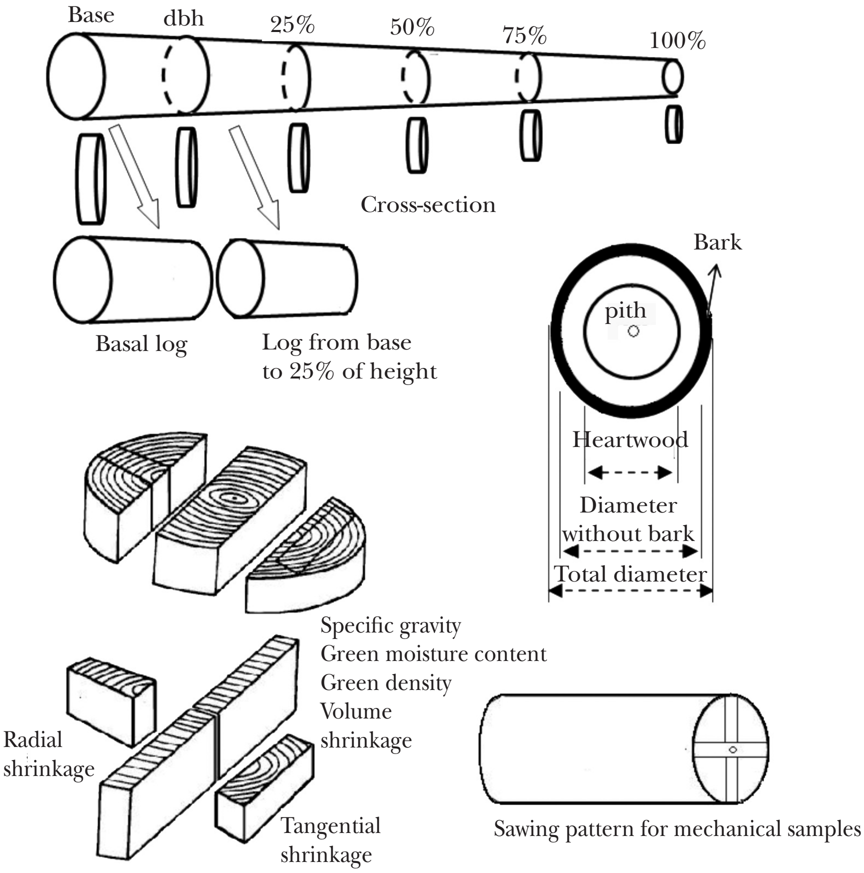

Figure 1 Sawing pattern used for wood properties

discs were then cut at 25, 50, 75 and 100% of commercial height (Figure 1). The north–south direction was marked on each stem cross-section and logged for identification later in the laboratory.

Heartwood, pith and bark percentage determination

On each disc from each height a cross-sectional line was drawn from north to south passing through the pith and another was marked perpendicular to the first, from east to west. Total diameter, diameter inside bark, diameters of pith and heartwood (HWC) (Figure 1), when different, were measured on the cross-sectional lines drawn in the two directions (north–south and east–west). Means for all diameters were calculated as the average of two cross-sectional measurements on each stem section. Total, heartwood and pith cross-sectional area were calculated as geometric circles and bark content was determined as the difference between total area and area without bark.

Physical and mechanical properties

A 3 cm wide block was cut along the centre (including the pith) of each disc and divided into two subsamples (cut into half) for studying the physical wood properties (Figure 1). Specific gravity (SG) was determined using both subsamples. The volume of each sample was defined as the volume of water it displaced when submerged, according to ASTM D2395-02 standards (ASTM 2003a). The wood density was calculated as green mass divided by green volume and it was renamed green density (GD) while the SG was calculated as oven-dry weight (105 °C, 48 hours) divided by green volume. GD gives unit of weight/volume (g cm^{-3}) and SG is unitless. The two logs taken from the base of the tree to 25% height (Figure 1) were used for determination of static bending (modulus of rupture (MOR) and modulus of elasticity (MOE)), compression parallel to grain (maximum crushing stress), shear parallel to grain (maximum shearing stress) and side janka hardness. A total of 18 samples per species were prepared per each test, following ASTM D-143-94 standards (ASTM 2003b).

Statistical analyses

Normality and the presence of anomalous data or outliers were examined for each variable. The variables transformed are indicated in the tables. A general statistical overview was performed for the different variables. Correlation analyses were used for evaluating the relationship between heartwood, sapwood and bark with stem height. An analysis of variance (ANOVA) was used for evaluating differences between species. Where statistical differences occurred, the means were compared using Tukey's test at 1.0% significance.

RESULTS AND DISCUSSION

Heartwood, pith and bark content

Heartwood was absent only in *A. acuminata* (Table 2). Heartwood was found only at less than 50% commercial height in *B. quinata, V. guatemalensis* and *T. amazonia* (Figure 2), and their means were 12.45, 8.52 and 7.18% respectively at dbh (Table 2). The mean HWC was moderate in *T. oblonga* and *S. macrophylla*, with 24.14 and 41.28% respectively at dbh (Table 2). Finally, there was a higher HWC in *A. mangium* and *C. lusitanica*, over 64% at dbh (Table 2) and over 50% at commercial height (Figure 2a). The significant decline in HWC was confirmed by regression analysis for all fast-growing species (Table 3), except for *T. oblonga* where no significant effect was found for tree height (Table 3). The estimation of HWC helps to define differences in durability and other wood characteristics (Wiemann & Williamson 1989). Low HWC was documented in some tropical plantation species, such as *T. grandis* (Pérez & Kanninen 2003, Moya & Pérez 2008) and *G. arborea* (Moya 2004). The decline of the HWC with tree height was confirmed in previous studies on *B. quinata* (Pérez *et al.* 2003), *A. mangium* (Lee *et al.* 1999) and *V. guatemalensis* (Moya *et al.* 2009). However, these researchers did not find the presence of heartwood in 9-year-old *T. amazonia* plantations in Costa Rica. The lower HWC or lack of heartwood, in contrary to our results, in some fast-growing tropical species shows that this tissue increases with tree age (Pérez *et al.* 2003).

Bark percentage (BP) varied between 7.12 and 20.38% of the cross-sectional area at dbh (Table 2). The lowest values were found in *C. lusitanica* and *A. acuminata*. Moderate values were found in *A. mangium*, *T. amazonia* and *T. oblonga*. The highest mean values were found in *S. macrophylla* and *B. quinata* (Table 2). Bark percentage tended to increase significantly with increasing stem height in all species (Table 3, Figure 2b), except for *A. mangium* where the BP decreased with tree height (Figure 2b). Different bark types have different physiological properties related to the ecology of the different tree species and provide different habitats for bark-living arthropods (Nicolai 1986). The thickness of the bark correlates with geographical factors, such as moisture availability, tree age and diameter classes (Sonmez *et al.* 2007). Although our research did not determine the effect of geographical position or soil moisture availability, it was possible to conclude that plantation species growing in dry sites (*B. quinata, T. amazonia, T. oblonga* and *S. macrophylla*) had the highest values in bark proportions. Conversely, the lowest values were found in species planted in wet sites (*A. acuminata, C. lusitanica* and *V. guatemalensis*). However, in *A. mangium* the BP was comparable with some dry species (Table 2).

Pith percentage (PP) did not change across the trunk in *S. macrophylla* (Figure 2c). It was possible to observe a very small hole in *C. lusitanica* and *B. quinata* at dbh and along the tree length, therefore the lower PP values (Figure 2c). Pith percentage often changed significantly with tree height, but in *C. lusitanica* and *A. mangium* there were no relationships with height (Table 3). Lower values of PP were also found in *A. acuminata, T. amazonia* and *T. oblonga* at dbh (Table 2). Some differences could be observed across the trunk. Non-significant relationship was determined in *A. mangium* (Table 3) but only small significant increments were observed in the PP for *T. amazonia* and *T. oblonga*. However, large differences were measured in the pith of *A. acuminata* (Figure 2c, Table 3). Although few studies have shown the negative effect of the presence of pith in hardwood (Moya *et al.* 2008), several references on softwood species have reported the effects of pith on wood quality (Timell 1986). The presence of pith diminishes both the amount and quality of wood products that can be obtained from log. In accordance with this, PP affects lumber quality in *V. guatemalensis, A. acuminata, A. mangium, T. amazonia* and *T. oblonga*. Fewer effects can be

Table 2 Tissue characteristics of trees and physical properties of eight fast-growth plantation species in Costa Rica

Wood property	*Alnus acuminata*	*Acacia mangium*	*Bombapcosis quinata*	*Cupressus lusitanica*	*Swietenia. macrophylla*	*Terminalia amazonia*	*Terminalia oblonga*	*Vochysia guatemalensis*
Heartwood (%)	Absent	64.85a (6.51)	12.45 e (10.94)	69.71 a (2.39)	41.28 b (9.13)	7.18 d (5.41)	24.14 c (14.13)	8.52 d (9.52)
Bark (%)	8.67 d (4.35)	14.32 b (2.97)	20.38 a (6.85)	7.12 d (1.22)	19.54 a (2.54)	11.16 c (3.14)	12.33 bc (2.68)	11.99 c (5.45)
Pith (%)	0.10 c (0.05)	0.16 b (0.04)	0.03 d (0.02)	0.03 d (0.003)	Absent	0.12 c (0.03)	0.09 c (0.02)	0.25 a (5.45)
Specify gravity	0.34 d (0.03)	0.45 c (0.04)	0.32 d (0.03)	0.43 c (0.03)	0.50 b (0.03)	0.49 b (0.06)	0.58 a (0.09)	0.32 d (0.02)
Initial MC (%)	95.19 c (8.41)	91.44 c (27.91)	157.01 a (32.55)	106.21 b (28.95)	67.46 e (4.52)	65.71 e (12.4)	71.52 d (7.66)	146.04 a (24.8)
Green density (g cm^{-3})	0.68 e (0.05)	1.06 a (0.05)	0.96 b (0.05)	1.05 a (0.07)	0.87 c (0.05)	0.81 d (0.09)	0.99 b (0.12)	0.89 c (0.07)
Radial shrinkage (%)	3.52 a (1.13)	2.59 b (0.61)	2.45 b (0.49)	3.24 a (0.99)	3.05 a (0.45)	3.34 a (0.88)	2.72 b (0.54)	2.53 b (0.50)
Tangential shrinkage (%)	6.79 a (0.44)	4.40 c (0.42)	3.18 e (0.31)	4.42 c (0.52)	4.09 d (0.91)	5.31 b (0.65)	4.87 bc (0.79)	6.93 a (0.56)
Volumetric shrinkage (%)	11.19 b (2.43)	13.24 a (2.33)	7.48 d (1.47)	7.29 d (1.24)	7.56 d (1.69)	9.92 c (5.74)	11.80 b (9.38)	13.16 a (2.09)
T/R ratio	1.92 b (0.72)	1.78 c (0.41)	1.34 d (0.30)	1.45 d (0.38)	1.35 d (0.25)	1.67 c (0.38)	1.38 d (0.29)	2.73 a (0.29)

MC = moisture content; n = 9. Values in brackets are standard deviations. Different letters within the same row mean statistically different at 99%. Specify gravity is a non-dimensional value. T/R ratio shrinking is ratio between tangential and radial shrinkages.

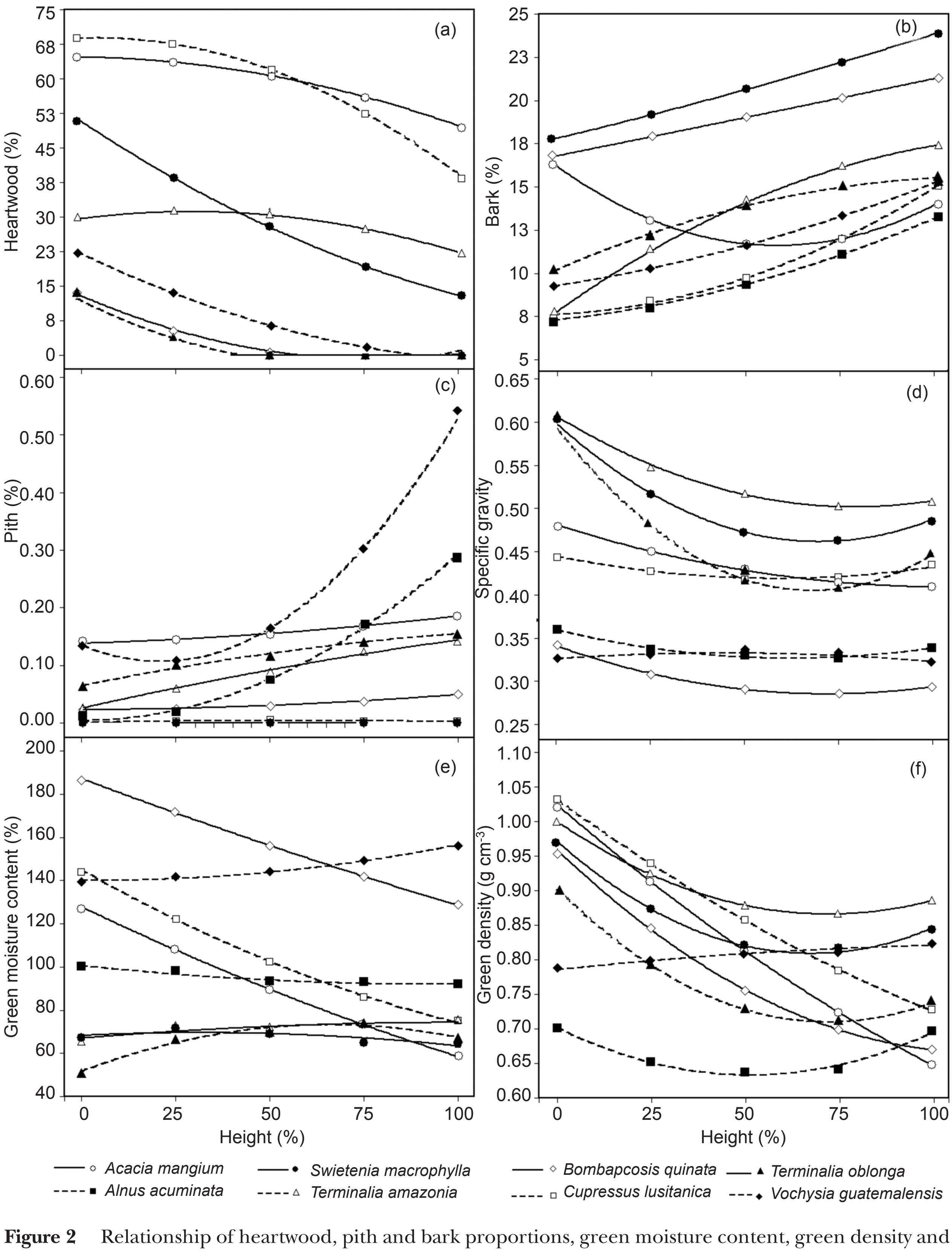

Figure 2 Relationship of heartwood, pith and bark proportions, green moisture content, green density and specific gravity with stem height in eight fast-growth plantation species in Costa Rica

found on lumber quality in *S. macrophylla*, *C. lusitanica* and *B. quinata*. On the other hand, pith is a typical tissue in many trees (Jane *et al.* 1970) and its size in relation to diameter can reduce with diameter increasing due to better plantation management, site, topography and other environmental conditions as well as tree height (Kellog & Barber 1981, Akachuku & Abolarin 1989, Moya *et al.* 2008).

Physical wood properties

Table 2 shows the mean values for physical properties at breast height. Figures 2d, e and f are the scattered values of SG, green moisture content (GMC) and GD respectively with tree height. Statistically significant differences were shown in Table 2 as well. Mean SG ranged from 0.32 to 0.58 at breast height (Table 2). The lowest values were found in *B. quinata* and *V. guatemalensis* (0.32) and *A. acuminata* (0.34). The highest value was found in *T. oblonga*. *Acacia mangium* and *C. lusitanica* had moderate values from 0.43 to 0.45. Meanwhile, an SG of almost 0.5 was measured in *T. amazonia* and *S. macrophylla*. The significant decline in SG associated with an increase in tree height (Figure 2d) was confirmed from regression analyses of *A. mangium*, *B. quinata*, *S. macrophylla*, *T. amazonia* and *T. oblonga* (Table 3, Figure 2d). However, non-significant relations were found for SG and tree height in *C. lusitanica*, *A. acuminata* and *V. guatemalensis* (Table 3, Figure 2d). Specific gravity is considered to be an indicator of timber strength and many others characteristics (Wiemann & Williamson 1989). *Vochysia guatemalensis*, *A. acuminata* and *B. quinata* timber could be associated with low strength resistance and probably low pulping production too, due to its low SG. Consequently, these species are not recommended for non-structural purposes. Conversely, for *T. oblonga* and *S. macrophylla*, which had the highest values of SG, superior mechanical properties could be expected. Finally, moderate mechanical resistance was found in *T. amazonia*, *A. mangium* and *C. lusitanica*. However, the mechanical properties or other wood properties related to SG must be carefully considered, especially in *T. oblonga*, *T. amazonia* and *S. macrophylla*, because the logs from the upper parts of the trunk had lower SG compared with the lower (Figure 2d).

Green moisture content ranged from 65.71 to 157.01% at dbh (Table 2). The lowest values were measured in *S. macrophylla*, *T. amazonia* and *T. oblonga*. The highest values were found in *B. quinata* and *V. guatemalensis*. The rest of the plantation species registered moderate

Table 3 Statistical parameters of relationships of wood properties with tree height in eight fast-growth plantation species in Costa Rica

Species	Heartwood percentage		Bark percentage		Pith percentage		Specify gravity		Initial moisture content		Green density	
	F-value	r^2	F-value	r^2	F-value	r^2	F-value	r^2	F-value	r^2	F-value	r^2
Acacia mangium	< 0.0001	0.50	0.0001	0.36	0.1985	0.07	< 0.0001	0.35	< 0.0001	0.80	< 0.0001	0.75
Alnus acuminata	Absent		<0 .0001	0.55	< 0.0001	0.81	0.1234	0.15	0.5119	0.05	0.2881	0.09
Bombacopsis quinata	< 0.0001	0.63	0.0002	0.34	< 0.0001	0.52	< 0.0001	0.56	< 0.0001	0.42	< 0.0001	0.64
Cupressus lusitanica	< 0.0001	0.87	< 0.0001	0.67	0.2064	0.07	0.0157	0.18	< 0.0001	0.78	< 0.0001	0.69
Swietenia macrophylla	< 0.0001	0.87	< 0.0001	0.64	Absent		< 0.0001	0.67	0.0032	0.24	< 0.0001	0.47
Terminalia amazonia	< 0.0001	0.85	< 0.0001	0.36	0.0011	0.28	< 0.0001	0.68	< 0.0001	0.39	< 0.0001	0.60
Terminalia oblonga	0.0107	0.19	< 0.0001	0.62	< 0.0001	0.50	< 0.0001	0.68	0.0598	0.13	< 0.0001	0.49
Vochysia guatemalensis	< 0.0001	0.78	< 0.0001	0.61	< 0.0001	0.71	0.7411	0.01	0.2886	0.06	0.7853	0.01

values of GMC, from 91.44 to 106.21%. No variation in GMC was found to be associated with tree height in *A. acuminata*, *T. oblonga* and *V. guatemalensis* (Table 3). A pattern of decline with tree height was found to be statistically significant in *B. quinata*, *C. lusitanica* and *A. mangium* (Table 3), but a slightly increasing pattern was found in *V. guatemalensis* and *T. oblonga* (Table 3, Figure 2e).

On the other hand, GD varied from 0.68 to 1.06 g cm^{-3} at dbh (Table 2). The highest values were found in *A. mangium* and *C. lusitanica*. Meanwhile, GD was almost 1.00 g cm^{-3} in *B. quinata* and *T. oblonga* at breast height and varied from 0.81 to 0.89 in *S. macrophylla*, *T. amazonia* and *V. guatemalensis*. *Alnus acuminata* was the plantation species with the lowest values of GD. Another important point to note is that DG decreased with tree height in all species (Figure 2f, Table 3), except for *A. acuminata* and *V. guatemalensis* which did not show correlation to tree height (Table 3).

Although there is limited interest in GD, it is related to industrial practice because it can be associated with the transportation of logs or fresh sawn timber (Walker 2006). Plantation wood with lower GD, such as *A. acuminata*, can be recommended as suitable for transportation process. In contrast, woods with higher GD, such as *A. mangium* and *C. lusitanica*, produce logs with the highest weight. Consequently, more energy is involved in any transportation process where wood is in green condition.

Green moisture content is associated with many drying properties, such as the drying rate or the presence of drying defects (Moya & Muñoz 2008). Thus, *B. quinata* and *V. guatemalensis*, with the highest values of GMC, can be recommended because of lower drying times. *Shorea macrophylla*, *T. amazonia* and *T. oblonga* showed medium drying times.

Radial shrinkage at breast height varied from 2.45 to 3.52% (Table 2). Values higher than 3% were found in *A. acuminata*, *C. lusitanica*, *S. macrophylla* and *T. amazonia;* values lower than 3% were found in other plantation species. Tangential shrinkage (TS) at dbh ranged from 3.18 to 6.93%. Volumetric shrinkage (VS) at the same height varied from 7.29 to 13.24%. The highest values of these physical properties were found in *V. guatemalensis* and *A. acuminata*. The lowest values were found in *B. quinata* for TS and in *C. lusitanica* for VS. The index of wood dimensional stability was the highest in *V. guatemalensis*, *A. acuminata* and *A. mangium*. While our results did not confirm that SG was a good indicator of wood shrinkage, it was found that plantation species with lower SG showed the highest values in TS and VS. The highest indices of dimensional stability were found in the same species (Table 2). We sampled trees from fast-growing plantations of less than 18 years old. Juvenile wood was reported in these species and so a high proportion of juvenile wood would probably be found in plantation species such as *V. guatemalensis* and *A. acuminata*. However, it is necessary to confirm this. The highest shrinkage values can be found when juvenile wood is present in wood with the lowest SG values. Juvenile wood tissue has high shrinkage because of the cellulose molecules in the cell wall which are oriented at a significant angle away from the along-the-grain direction. This results in higher shrinkage values compared with the values observed in mature wood (Zobel & Sprague 1998)

Mechanical properties

The mean values for the mechanical properties of eight different plantation species are shown in Table 4. *Swietenia macrophylla* consistently yielded high values for most mechanical tests. It did not show the highest values in MOE in bending, shear strength in radial direction, axial janka hardness or nail holding strength. *Terminalia oblonga*, a plantation species, also had high mechanical properties. Although *T. oblonga* showed higher SG than *S. macrophylla* (Table 2, Figure 2), its mechanical properties were lower in resistance than *S. macrophylla* (Table 4). On the other hand, *V. guatemalensis* had the lowest values in mechanical properties and *B. quinata* had low values as well. The values of SG agreed with those of mechanical resistance. For example, *V. guatemalensis* and *B. quinata* demonstrated lower SG and lower mechanical properties. Confusing patterns were found in *A. mangium*, *A. acuminata*, *C. lusitanica* and *T. amazonia*; some values were highest in some species, but the lowest resistance was found in other wood properties. For example, 17.9 MPa was the mean compression strength parallel to fibre in *T. amazonia*, but the mean for *C. lusitanica* was 14.3 MPa. Disparate results were detected for shear parallel to fibre. *Cupressus lusitanica* had higher values than *T. amazonia* (Table 4).

Table 4 Mechanical wood properties of eight fast-growth plantation species at 12% moisture content

Mechanical property		*Alnus acuminata*	*Acacia mangium*	*Bombapcosis quinata*	*Cupressus lusitanica*	*Swietenia macrophylla*	*Terminalia amazonia*	*Terminalia oblonga*	*Vochysia guatemalensis*
Compression strength (MPa)	//	29.0 c (14.43)	34.0 bc (33.72)	8.7 f (22.89)	14.3 e (15.6)	48.0 a (10.84)	17.9 d (12.01)	37.5 b (8.43)	21.3 d (13.12)
	⊥	15.6 d (18.03)	24.0 c (25.15)	10.7 e (24.01)	24.1 d (16.54)	47.2 a (15.02)	22.3 c (22.31)	35.3 a (11.64)	14.5 d (15.82)
Tension strength ⊥ to fibre (MPa)	Tangential	4.0 a (21.89)	3.0 abc (35.97)	1.8 cd (23.90)	1.6 d (28.24)	3.0 ab (42.02)	2.3 bcd (41.00)	2.7 ac (22.21)	2.1 bcd (29.35)
	Radial	2.6 a (31.18)	2.8 a (32.78)	1.0 c (26.10)	1.4 c (29.96)	2.6 a (43.54)	1.7 b (31.97)	2.8 a (24.25)	1.6 d (24.22)
Tension strength (MPa)	//	67.7 bc (24.38)	89.7 a (20.79)	43.0 d (32.93)	52.2 cd (38.75)	74.6 ab (32.42)	56.7 bcd (27.22)	65.1 bc (28.5)	39.4 d (27.74)
Static bending	MOR (MPa)	51.9 c (19.29)	78.4 ab (12.22)	35.8 d (20.07)	57.6 c (18.45)	89.7 a (18.43)	74.6 b (15.78)	82.3 ab (8.85)	40.4 d (10.32)
	MOE (GPa)	7.7 c (23.08)	12.31 a (10.09)	5.6 e (19.93)	7.6 c (27.21)	9.48 b (15.22)	11.91 a (9.04)	8.07 b (13.72)	6.41 d (10.7)
Shear strength // to fibre (MPa)	Tangential	9.1 bc (15.04)	9.9 ab (10.65)	5.3 d (13.06)	10.1 a (12.90)	8.7 ab (14.31)	9.4 ab (28.61)	8.4 b (9.11)	6.9 c (15.17)
	Radial	7.9 b (21.33)	9.6 a (15.21)	4.7 d (17.11)	9.4 c (15.38)	7.9 b (11.61)	7.5 b (21.57)	7.6 b (7.87)	6.3 c (16.43)
Cleavage (MPa)	Tangential	0.87 a (22.56)	0.49 bc (27.47)	0.26 c (23.68)	0.23 c (37.12)	0.65 ab (16.28)	0.37 c (31.80)	0.69 ab (25.94)	0.61 b (35.32)
	Radial	0.59 ab (30.65)	0.45 bc (32.06)	0.30 d (18.54)	0.27 d (21.53)	0.49 ab (35.18)	0.34 cd (21.46)	0.73 a (16.89)	0.59 ab (24.62)
Janka hardness (N)	Axial	14 .7 d (24.05)	39.8 a (21.01)	15.7 cd (22.00)	29.8 b (21.66)	29.6 b (26.22)	38.4 a (25.39)	28.0 b (21.46)	18.4 c (15.07)
	Lateral	19.1 b (17.82)	29.0 a (18.04)	10.0 c (29.42)	18.7 b (22.24)	31.8 a (18.50)	22.5 b (40.03)	33.8 a (12.94)	10.3 c (34.19)
Nail holding strength (N)	Axial	2.38 b (42.92)	2.27 b (31.84)	1.69 b (24.96)	3.65 a (30.71)	3.53 a (37.41)	4.45 a (37.97)	4.76 a (22.25)	1.92 b (28.79)
	Lateral	1.92 d (33.56)	3.13 c (29.10)	2.00 d (19.87)	4. 84 ab (21.69)	3.67 bc (26.12)	5.81 a (37.79)	3.92 b (20.91)	2.02 d (25.25)

Log_{10} transformations were applied for compression strength, shear strength in radial direction, axial janka hardness and nail holding strength. Square root transformation was applied for MOR in bending and lateral janka hardness. Values in parentheses are standard deviations. // A = parallel to fiber, ⊥ = perpendicular to fibre. Different letters are statistically different at 99%.

Variability in wood properties, measured by variable coefficient can be important in both production and consumption of wood products (USDA 2003). The variable coefficient ranged from 7.87 to 43.54% (Table 4). The lowest values measured were for shear strength parallel to fibre in *T. oblonga* and the highest values were for tension strength perpendicular to fibre in *S. macrophylla*. Lower variable coefficients were found in the compression perpendicular to fibre (11.64–25.15%), MOR (8.85–20.07%), and MOE (9.04–23.08%) in bending, shear strength parallel to fibre in radial direction (7.87–21.60%), and axial janka hardness (15.07–26.22%). Conversely, higher variable coefficients were determined for tension strength perpendicular to fibre in tangential directions (21.89–42.02%), 24.22–43.54% perpendicular to fibre in radial directions and 20.79–38.75% for parallel to fibre.

Coefficients of variation (CV) for approximately 50 species growing in the United States of America which were presented in Tables 4–6 of Wood Handbook (USDA 2003) were compared with our study. The values of CV obtained in fast-growing plantations in Costa Rica for bending, compression and hardness strength were comparable with the values reported for US species. However, the CVs found for tension (perpendicular to fibre in tangential and radial directions, and parallel to fibre) and shear strengths in our study were slightly higher than those reported for the US species.

Previous studies on wood mechanical properties of forest species in Latin America suggest a great variability among species and countries. However, many researchers suggest that trees growing in plantation conditions produce wood with the lowest wood properties, such as specific gravity and other wood property variables (Zobel & Sprague 1998). For example, *T. amazonia* trees from natural forests in Panama (Llach 1971), Nicaragua (González *et al.* 1973), Bolivia, Venezuela and Colombia (Keenan & Tejada 1987), and Honduras (Shupe *et al.* 2005), among others, were reported to have superior mechanical properties to those from the forest plantations evaluated in the present study. In the case of *V. guatemalensis*, trees growing in natural forests in La Ceiba (Honduras) showed lower mechanical properties in a study by Sotela and Carpio (1991) compared with those in the forest plantations observed in the present study. In contrast, similar studies carried out in Panama (Llach 1971), Nicaragua (González *et al.* 1973), Honduras (Shupe *et al.* 2005) and Costa Rica (Tuk 1980) reported higher values than our results with plantation trees. These divergent results suggest a probable influence of site and environmental conditions on wood quality. Zobel and Van Buijtenen (1989) suggest that large structure variations are produced by changes in climate, site and management characteristics as a product of these extrinsic factors influencing various activities.

Although lower wood properties were demonstrated compared with trees growing in natural conditions, wood properties, especially SG and mechanical properties, can increase with tree age. Many molecular and physiological changes occur in the vascular cambium during the ageing process (Plomion *et al.* 2001). For example, in the adult stage, the xylem produce cells with thicker walls compared with those produced in the juvenile phase (Horacek *et al.* 1999). Thus, an increase of SG and mechanical properties with ageing of a tree could be an area for study in fast-growing plantation species so as to evaluate whether there is an observed increase in these properties.

CONCLUSIONS

Juvenile trees of six fast-growing species (*A. acuminata*, *B. quinata*, *T. amazonia*, *T. oblong*a and *V. guatemalensis*) utilised in Costa Rica showed HWC levels lower than 41% at dbh. However, HWC was less than 64% in *C. lusitanica* and *A. mangium*. A decrease with tree height was found in all species. On the other hand, BP varied from 7.12 to 20.38% and this percentage decreased with tree height. Meanwhile, pith diameter was nil in *S. macrophylla*. Lower PP was measured in *C. lusitanica* and *B. quinata* and the highest values, in the rest of the species. Increments with tree height were only observed in *T. amazonia* and *T. oblonga*.

The significant decrease in SG with increasing tree height was observed in *A. mangium*, *B. quinata*, *S. macrophylla*, *T. amazonia* and *T. oblonga*. However, no significant relationship was found for SG with height in *C. lusitanica*, *A. acuminata* and *V. guatemalensis*. No variation in GMC was found with tree height in *A. acuminata*, *T. oblonga* and *V. guatemalensis*, but decreases in GMC with tree height were shown in *B. quinata*, *C. lusitanica* and *A. mangium*. Slight increase in GMC was observed in *V. guatemalensis* and *T. amazonia*. Green density decreased with tree height in all species except for *A. acuminata* and *V. guatemalensis*.

Swietenia macrophylla consistently yielded high values for most mechanical tests. *Terminalia oblonga* was a plantation species with high values for mechanical properties. The lowest mechanical properties were observed in *V. guatemalensis* and *B. quinata*. Inconsistent results were found for *A. mangium*, *A. acuminata*, *C. lusitanica* and *T. amazonia*. The variation coefficient ranged from 7.87 to 43.54%. The lowest values were measured for shear strength parallel to fibre in *T. oblonga* and the highest, for tension strength perpendicular to fibre in *S. macrophylla*. In contrast, higher variation coefficients were determined for tension strength.

ACKNOWLEDGEMENTS

The authors wish to thank the Vicerrectoría de Investigación y Extensión of the Instituto Tecnológico de Costa Rica (ITCR), Precious Woods of Central America (MACORI), Ecodirecta Groups and Ganadera Barza SA Escuela de Agricultura y Ganadería del Tropico Humedo (EARTH) for support.

REFERENCES

Akachuku AE & Abolarin DA. 1989. Variations in the pith eccentricity and ring width in teak (*Tectona grandis* L.F.). *Trees* 3: 111–116.

ASTM (American Society for Testing and Materials). 2003a. *Standard Test Methods for Specific Gravity of Wood and Wood-based Materials*. ASTM D2395-02 Reproved 2000. Volume 04–10. ASTM, Philadelphia.

ASTM (American Society for Testing and Materials) 2003b. *Test Methods for Small Clear Specimens of Timber*. ASTM D 143-94. Reproved 2000. Volume 04–10. ASTM, Philadelphia.

Barrantes A & Castro G. 2007. *Usos y Aportes de la Madera en Costa Rica* (*Estadísticas 2006*). Oficina Nacional Forestal, San José.

Butterfield R, Crook R, Adams R & Morris R. 1993. Radial variation in wood specific gravity, fiber length and vessel area for two Central American hardwoods; *Hyeronima alchorneoides* and *Vochysia guatemalensis*: natural and plantation-grown trees. *IAWA Journal* 14: 55–64.

González E & Fisher R. 1994. Growth of native forest species planted on abandoned pasture land in Costa Rica. *Forest Ecology Management* 70: 159–167.

González E & Fisher R. 1998. Variation in selected wood properties of *Vochysia guatemalensis* from four sites in Costa Rica. *Forest Science* 44: 185–191.

González G, Wiessel C & Chavarri G. 1973. *Propiedades y Usos de Quince Especies Maderables del Nordeste de Nicaragua*. FO: SF/NIC 9. Informe Técnico 9. Gobierno de Nicaragua, Managua.

Horacek P, Slezingerova J & Gandelova L. 1999. Effect of environment on the xylogenesis of Norway spruce (*Picea abies* [L.] Karst.). In Winner R & Vetter RE (Eds.) *Tree-Ring Analysis: Biological, Methodological and Environmental Aspects*. CAB International, England.

Jane FE, Wilson K & White DJ. 1970. *The Structure of Wood*. Black, London.

Kellog R & Barber F. 1981. Stem eccentricity in coastal western hemlock. *Canadian Journal of Forest Research* 11: 714–718.

Keenan FJ & Tejada M. 1987. *Maderas Tropicales Como Material de Construcción en los Países del Grupo Andino de América del Sur*. Centro Internacional de Investigaciones para el Desarrollo, Ottawa.

Lee SS, Teng SY, Lim MT & Razali AK. 1999. Discolouration and heart rot of *Acacia mangium* Willd.—some preliminary results. *Journal of Tropical Forest Science* 1: 179–177.

Llach L. 1971. *Propiedades físicas y mecánicas de ciento trece especies maderables de Panamá*. Parte 3. Universidad de Costa Rica, Curridabat, Costa Rica.

Laurila R. 1995. Wood properties and utilization potential of eight fast-growing tropical plantation tree species. *Journal of Tropical Forest Science* 1: 209–221.

Moya R. 2000. Comportamiento y rendimiento en aserrío de trozas de *Terminalia amazonia* de 6 años de edad provenientes de la zona sur de Costa Rica. *Revista Forestal Centroamericana* 29: 14–19.

Moya R. 2004. Wood of *Gmelina arborea* in Costa Rica. *New Forest* 28: 299–307.

Moya R, Araya L & Vílchez B. 2008. Variation in the pith parameter of *Gmelina arborea* trees from fast growth plantations in Costa Rica. *Annals Forest Science* 65: 612–621.

Moya R, Leandro L & Murillo O. 2009. Wood characteristics of three native species: *Terminalia amazonia*, *Vochysia guatemalensis* and *Hyeronima alchorneoides* growing in fast-growth plantations in Costa Rica. *Revista Bosques* 30: 78–87.

Moya R & Muñoz F. 2008. Wet pockets in kiln-dried *Gmelina arborea* lumber. *Journal of Tropical Forest Science* 20: 48–56.

Moya R & Pérez D. 2008. Effect of physical and chemical soil properties on physical wood characteristics of *Tectona grandis* plantations in Costa Rica. *Journal of Tropical Forest Science* 20: 147–155.

Moya R & Tomazello M. 2008. Variation in the wood anatomical structure of *Gmelina arborea* trees at different ecological conditions in Costa Rica. *Revista Biologia Tropical* 56: 689–704.

Moya R, Valenzuela L & Salazar F. 2002. Efecto de la fertilización de la pradera sobre la densidad básica de *Pinus radiata*. D. Don. *Revista Investigación Agraria: Sistemas y Recursos Forestales* 11: 182–192.

Murillo O, Obando G, Badilla J & Sánchez S. 2001. Perspectivas en las zonas altas de Costa Rica. *Biocenosis* 15: 66–71.

Nicolai V. 1986. The bark of trees: thermal properties, microclimate and fauna. *Oecologia* 69: 1432–1439.

Pérez D & Kanninen M. 2001. Stand growth scenarios for *Bombacopsis quinata* plantations in Costa Rica. *Forest Ecology and Management* 177: 427–439.

Pérez D & Kanninen M. 2003. Heartwood, sapwood and bark content, and wood dry density of young and mature teak (*Tectona grandis*) trees grown in Costa Rica. *Silva Fennica* 37: 45–54.

Pérez D & Kanninen M. 2005. Stand growth scenarios for *Tectona grandis* plantations in Costa Rica. *Forest Ecology Management* 210: 425–441.

Pérez D, Kanninen M, Matamoros F, Fonseca W & Chaves E. 2003. Heartwood, sapwood, and bark content of *Bombacopsis quinata* in Costa Rica. *Journal of Tropical Forest Science* 16: 318–327.

Petit B & Montagnini F. 2004. Growth equations and rotation ages of ten native tree species in mixed and pure plantations in the humid neotropics. *Forest Ecology and Management* 199: 243–257.

Plomion C, Leprovost G & Stokes A. 2001. Wood formation in trees. *Plant Physiology* 127: 1513–1523.

Shupe TF, Aguilar RT, Vlosky RT, Belisle M & Chavez A. 2005. Wood properties of selected lesser-used Honduran wood species. *Journal of Tropical Forest Science* 17: 438–446.

Sotela J & Carpio MI. 1991. *Vochysia Guatemalensis en Centroamérica*. Informe INII-63-1991. Universidad de Costa Rica, Curridabat, Costa Rica.

Sonmez T, Keles S & Tilki F. 2007. Effect of aspect, tree age and tree diameter on bark thickness of *Picea orientalis*. *Scandinavian Journal of Forest Research* 22: 193–197.

Timell TE. 1986. *Compression Wood in Gymnosperms*. Volumes 1–3. Springer Verlag, New York.

Tuk J. 1980. *Clasificación y Normalización de Maderas para uso Estructural*. Instituto Tecnológico de Costa Rica, Cartago.

USDA (United States Department of Agriculture). 2003. *Wood Handbook*: *Wood as an Engineering Material*. General Technical Report 113. Forest Products Laboratory, Wisconsin.

Walker J. 2006. *Primary Wood Processing: Principles and Practice*. Springer Verlag, New York.

Wiemann MC & Williamson G. 1989. Wood specific gravity gradients in tropical dry and montane rain forest trees. *American Journal Botany* 76: 924–928.

Zobel B & Sprague J. 1998. *Juvenile Wood in Trees*. Springer-Verlag, New York.

Zobel B & Van Buijtenen B. 1989. *Wood Variation: Its Causes and Control*. Springer Verlag, New York.