EFFECTS OF PHYSICAL AND CHEMICAL SOIL PROPERTIES ON PHYSICAL WOOD CHARACTERISTICS OF *TECTONA GRANDIS* PLANTATIONS IN COSTA RICA

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MOYA, R. & PEREZ, D. 2008. Effects of physical and chemical soil properties on physical wood characteristics of *Tectona grandis* plantations in Costa Rica. A total of 23 plantations with ages between 7 and 15 years were selected in the north and north-west regions of Costa Rica, covering a wide range of soil fertilities. Texture analysis included the determination of clay, silt and sand content, apparent density, water retention percentage, water useful percentage, and retention at 15 and 0.33% bars. Normal tangential shrinkage and normal radial shrinkage were the most correlated variables with soil characteristics, while the less correlated variables were specific gravity and normal volumetric shrinkage. Correlation coefficients were highly significant ($\alpha = 0.05$) but low (< 0.64), probably influenced by the range of climatic and soil conditions. Soil characteristics (physical and chemical) had no influence on wood properties. A large range of soils in Costa Rica is suitable for growing teak without detrimental effect on certain wood properties.

Keywords: Bark, heartwood, pith, specific gravity, shrinkage, wood quality

MOYA, R. & PEREZ, D. 2008. Kesan sifat fizikal dan kimia tanah terhadap ciri fizikal kayu daripada ladang *Tectona grandis* di Costa Rica. Sebanyak 23 ladang antara usia 7 tahun hingga 15 tahun dipilih daripada utara dan barat laut Costa Rica untuk kajian. Kawasan ini meliputi julat kesuburan tanah yang luas. Analisis tekstur melibatkan penentuan kandungan-kandungan lempung, lodak dan pasir, ketumpatan ketara, peratusan penahanan air, peratusan kegunaan air serta penahanan pada 15 bar dan 0.33% bar. Kecutan tangen normal dan kecutan jejari normal paling banyak berkorelasi dengan ciri-ciri tanah manakala graviti tentu dan kecutan volumetrik normal paling rendah korelasinya. Pekali korelasi sangat signifikan ($\alpha = 0.05$) tetapi nilainya rendah (< 0.64). Keadaan ini mungkin dipengaruhi oleh iklim dan keadaan tanah. Ciri-ciri tanah (fizikal dan kimia) tidak mempunyai kesan terhadap ciri-ciri kayu. Tanah di Costa Rica yang mempunyai kesuburan berbeza-beza sesuai untuk penanaman pokok jati tanpa memberi kesan kepada beberapa ciri-ciri kayu.

INTRODUCTION

Tectona grandis has been largely planted in many tropical regions including Latin America, Asia, Africa and Oceania, covering approximately six million hectares (FAO 2006). Teak plantations are being managed under new concepts of fast growth and high productivity (Monteuuis & Goh 1999, Bermejo *et al.* 2004, Perez & Kanninen 2005a). However, the high demand for incorporating new planting sites has led to the establishment of plantations on poor soils, resulting in a very low performance, high management costs and additional deterioration of soils due to high intensive culture practices (Pal & Husen 2004, Nath *et al.* 2005, Alvarado 2006, Webb *et al.* 2006).

Teak wood is known in the international market for its durability, high resistance to chemicals and unique esthetical properties (Tewari 1999). Wood formation is attributed to many factors including site, environment, stand conditions, management, genetics and age (Zobel & Van Buijtenen 1989, Saranpää 2003). Variation of teak wood properties (particularly wood density) with different factors (thinning, pruning, genetic material, spacing, age, etc.) has been reported extensively in different regions of the world (Bhat 1998, Bhat & Florence 2003, Moya *et al.* 2003, Perez & Kanninen 2003, Windeisen *et al.* 2003, Bhat & Priya 2004, Dzifa *et al.* 2004, Perez & Kanninen 2005b, Viquez & Perez 2005).

Variations in wood quality with tree growth are strongly related to physical and chemical properties of the soil (Rigatto *et al.* 2004). A low wood density may be obtained on sites with favourable soil properties for stand growth (particularly tree diameter) with a consequent low quality for structural uses (Cutter *et al.* 2004).

Other studies on teak in Central America reported the relationship of wood production with physical and chemical characteristics of soils. Alvarado and Fallas (2004), and Ugalde *et al.* (2005) stated that a reduction of 3% occurs in the average stand growth when the pH levels fall below 6, while an optimum growth rate takes place when the calcium level is superior to 68% on teak plantations in Costa Rica and Panama.

No detailed description of soil properties were reported in studies related to wood characteristics, as 'site location' is given as unique reference on most cases. In relation to this, Kokutse *et al.* (2004) found that the heartwood percentage, wood density, elastic dynamic module and moisture content depend on site location.

Few studies reported the effects of chemical or physical soil characteristics on wood quality (Aguilar-Rodriguez *et al.* 2006), as reviewed by Zobel and Van Buijtenen (1989) for species other than teak. Recently, Dünisch and Bauch (1994) reported the effect of water content and mineral nutrients of soil on the size of growth rings for *Picea abies*. Rigatto *et al.* (2004) found soil chemical properties affecting wood quality and physical properties affecting the production of cellulose in *Pinus tadea*, as evidenced by the low wood density, short fibre, wide cellular wall, high contents of extractives and lignin, and low contents of cellulose. Yáñez-Espinosa *et al.* (2001) found that soil texture and water salinity are highly correlated with anatomical characteristics of four species in a mangrove forest community in Mexico.

Mattson and Bergsten (2004) reported a reduction in wood density by soil mechanization, as a response to more suitable conditions for a faster tree growth rate. Yañez-Espinosa *et al.* (2004) found that *Laguncularia racemosa* presented a high frequency of vessels, abundant parenchyma, and shorter fibres and vessels, related to sites with low salinity. Other fibre characteristics such as flexibility, rigidness, as well as Peteri and Runke coefficients were not affected by site conditions.

Very few studies have been carried out on teak plantations comprehending the relationship of wood properties with soil characteristics. Most of them have been carried out by private companies and are still unpublished. The aim of the present study was to analyze the effects of soil chemical and physical characteristics on different teak wood properties in the north region of Costa Rica.

MATERIALS AND METHODS

Study area

A total of 23 plantations with ages between 7 and 15 years were selected in the north and north-west regions of Costa Rica, covering a wide range of soil fertilities (Table 1). The north-west region reports an annual precipitation of between 1500 and 2000 mm, an average annual temperature of 25–28 °C, and a strong dry season between January and April (Bolaños & Watson 1993). The northern region, classified as wet tropical forest, reports an annual precipitation of between 2800 and 5000 mm, an average annual temperature of 20–25 °C, with a short dry season in February and March.

Sample plantations

The 23 sampled plantations were owned by three different private companies located within the study area. Stand density varied between 160 and 580 trees per ha. Dasometric variables were obtained from the different sample plot databases previously established and continuously measured by the companies (Table 1).

Soil study

A soil profile of 1 × 1 × 1 m size was established on each plantation, procuring to place each profile within the most representative site area and next to a sample plot. Samples from the upper layer (first 20 cm) of the soil profile were taken for determining the apparent density, water retention percentage and the water useful percentage. In addition, the depth of the first layer and effective depth were determined on each soil profile. Samples were taken for further texture and chemical analyses.

Table 1 Average dasometric variables and site locations of each plantation evaluated

Site code	Age (years)	Latitude (N)	Longitude (W)	Tree height (m)	dbh (cm)	Stand density (trees ha^{-1})	Basal area (m^2 ha^{-1})
1	14	N 10° 45' 42"	W 84° 27' 15"	25.80	25.60	264	13.59
2	14	N 10° 45' 35"	W 84° 27' 41"	16.90	16.90	226	5.07
3	14	N 10° 48' 43"	W 84° 26' 20"	22.10	25.30	264	13.27
4	14	N 10° 48' 52"	W 84° 25' 59"	15.50	16.30	245	5.11
5	7	N 10° 51' 21"	W 84° 29' 54"	18.07	19.90	396	12.32
6	7	N 10° 51' 16"	W 84° 30' 19"	14.89	15.34	377	6.97
7	14	N 10° 59' 03"	W 84° 45' 04"	19.10	22.30	188	7.34
8	14	N 10° 59' 09"	W 84° 45' 05"	18.10	25.40	151	7.65
9	9	N 10° 58' 46"	W 84° 44' 45"	16.13	19.37	318	9.37
10	11	N 11° 05' 24"	W 85° 27' 36"	17.70	21.30	300	10.69
11	11	N 11° 04’ 48"	W 85° 27' 00"	15.90	18.90	440	12.34
12	10	N 11° 06' 36"	W 85° 28' 12"	18.00	22.50	440	17.49
13	10	N 11° 06' 00"	W 85° 28' 12"	15.00	18.90	520	14.59
14	8	N 11° 12' 00"	W 85° 35' 24"	13.10	17.80	580	14.43
15	8	N 11° 12' 00"	W 85° 36' 00"	16.50	21.10	500	17.48
16	10	N 11° 11' 24"	W 85° 37' 48"	14.10	18.70	460	12.63
17	10	N 11° 11' 24"	W 85° 37' 12"	19.10	25.10	320	15.83
18	15	N 11° 09' 36"	W 85° 41' 24"	22.50	26.50	300	16.55
19	15	N 11° 09' 00"	W 85° 41' 24"	21.60	24.20	320	14.72
20	13	N 09° 50' 49"	W 85° 10' 52"	23.20	25.40	172	8.70
21	13	N 09° 50' 18"	W 85° 11' 02"	23.30	27.40	160	9.40
22	15	N 09° 49' 19"	W 85° 14' 40"	22.00	23.20	328	13.90
23	15	N 09° 49' 56"	W 85° 14' 32"	22.10	24.20	338	15.50

Texture analysis consisted of the determination of clay, silt and sand content, apparent density, water retention percentage, water useful percentage, retention at 15 and 0.33% bars, according to the method by Forsythe (1985). The chemical analysis of the first soil layer was carried out using the methods of Diaz-Romeu and Hunter (1978), Briceño and Pacheco (1984) and Bertsh (1987).

Potassium chloride (KCl) was used as extracting medium for the determination of the exchangeable acidity, and calcium (Ca) and magnesium (Mg) content. A spectrum photometer of atomic absorption ‘Analisis 300’ was used for determining the content of phosphorus (P), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and potassium (K). The cation exchange capacity was measured by spectrum photometer of AA (CIA-SC09-01-02-2005) and the acidity saturation was determined by the exchange acidity.

Sample trees

A total of three average trees (with mean dbh, straight stem, normal branching and without pests or diseases) were selected from neighbouring areas of each soil profile. North orientation was marked on each tree prior to harvesting. A stem cross-sectional disk was taken at breast height (1.13 m) and placed in plastic bags for further laboratory analysis.

The heartwood, bark and pith percentages were determined on each stem disc. The heartwood and pith diameter was calculated as the average of two cross-sectional measurements (direction north–south and east–west). The total mean diameter (with and without bark) was calculated following the same procedure. The bark thickness was defined as the difference between diameter with and without bark. The area of each component was determined as a geometric circle and the corresponding percentages calculated by simple mathematical calculus.

Physical properties were determined following the international norms of ASTM D-143 (ASTM 2003a). Properties include radial, tangential, and volumetric shrinkages (normal, i.e. from green to 12% of moisture content, and total, i.e. from green condition to oven-dried condition), green moisture content and specific gravity (basic and air dried). Each stem disc (3 cm width) was sectioned following the pattern shown in Figure 1. The weight and volume of each subsample were determined in green condition according to the American Standard Testing Materials D-2395-02 (ASTM 2003b). Next, all samples were conditioned at 65% relative humidity and 22 °C (air-dry condition) and the weight and volume were measured for a second time. Oven-dried weight and volume were measured a third time once the samples were oven dried (105 °C for 24 hours).

The wood density in green condition was calculated as weight divided by volume, while the moisture content was calculated as the difference between green and dry weights and divided by dry weight, both values expressed as percentages. The specific gravity was calculated as the oven-dried weight divided by volume in green condition (basic) and air-dried weight divided by volume in green condition (air condition). The volume shrinkage was determined as the difference between green and dry volume, and divided by green volume.

Statistical analysis

A Pearson correlation matrix was used for determining the most correlated physical properties. Selected variables for comparison were specific gravity, tangential, radial and volumetric normal shrinkages, green density, moisture content, and heartwood, bark and pith percentages. Variables were correlated with the physical and mechanical soil properties. Forward stepwise analysis was carried out to define the priority soil variables had on wood properties the most. Surface analyses were performed as graphical support to different polynomial correlations, aiming at interpreting the most important variable interactions.

RESULTS

Correlations between wood properties

The Pearson correlation matrix showed important correlations (r > 0.50) between wood normal and total shrinkage (tangential, radial and volumetric), specific gravity in green condition with specific gravity at different moisture conditions, and green density with moisture content. Heartwood, bark and pith percentages were not correlated with wood characteristics such as shrinkage, specific gravity, green density or moisture content.

Relationship between physical wood properties and soil characteristics

Normal tangential shrinkage and normal radial shrinkage were the most correlated variables with soil properties, while the least correlated variables were specific gravity and normal volumetric shrinkage (Table 2). Correlation coefficients were highly significant ($\alpha = 0.05$) but low (< 0.64), probably influenced by the wide range of climatic and soil conditions.

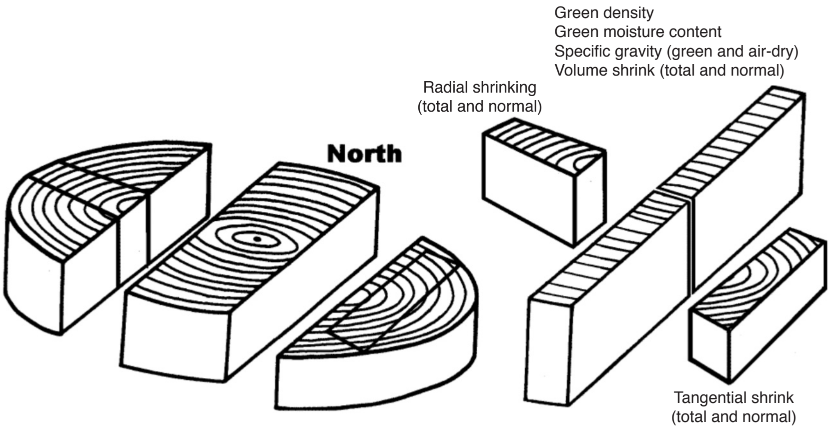

Figure 1 Sawing pattern used on each stem section for the analysis of mechanical wood properties

Wood properties were influenced by few physical and chemical soil properties, except for normal radial shrinkage, which was correlated with six other variables (Table 3). Multiple correlation analysis (Table 3) showed that relationships between wood properties and soil characteristics were roughly explained by the different model parameters ($r < 0.83$).

The phosphorus in the soil explained up to 30% of the normal tangential shrinkage, complemented by the silt content representing 9.5% of the total variation, while variations in normal radial shrinkage were explained by iron content (40%) and by silt content (15.1%). Green density was explained only in 8.5% by the zinc content, while the heartwood content was related to dbh (30.6%) and plantation density (6.5%) but not to any soil characteristic. Pith percentage, a considerably important wood property (or wood defect) was slightly correlated with tree age (16.7%) and calcium content (14.9%).

The low correlation coefficients suggest that wood properties cannot be fully explained by soil characteristics and that other factors may have a larger influence on them (genetics, growth rate, plantation management, dry season periods, precipitation, climate).

The most significant relationships were plotted for ease of interpretation. The wood specific gravity was highest in plantations older than 12 years and on sites with copper lower than 12 mg l^{-1} (Figure 2a). The normal tangential

Table 2 Pearson correlation coefficients for the relationship between wood properties and soil characteristics

Variable		Wood property								
		SG	NTS	NRS	NVS	GD	MC	Hw%	Pith%	Bark%
Physical characteristic	D			0.300*		0.250*				-0.314**
	ED		0.484**	0.520**					-0.237*	
	Ret33		-0.327**	-0.384**						0.288*
	Ret15					0.249*				
	WUP		-0.415**	-0.500**						0.288**
	AD		0.381**	0.460**						-0.255*
	S%		-0.350**	-0.304*						0.317**
	L%		0.465**	0.529**				-0.636**		
	C%									
Chemical characteristic	pH		0.370**	0.375**						
	EA		-0.347**						0.338**	
	Ca		0.425**	0.536**					-0.343**	
	Mg		0.428**	0.581**					-0.335**	
	K		0.210							
	CEC		0.432**	0.562**					-0.344**	
	AS		-0.376**	-0.276*					0.374**	
	P		-0.551**	-0.608**					0.366**	
	Zn					0.292*	0.334**			
	Cu	-0.280*					0.306*			
	Fe		-0.499**	-0.636**						
	Mn		-0.416**	-0.397**					0.289*	

Missing values correspond to no statistically significant values. ** Statistically significant at 99% confidence; * Statistically significant at 95% confidence. D = depth of first layer; ED = effective depth (of soil); Ret33 = water retention at 0.33% bars; Ret15 = water retention at 15 bars; WUP = water utility percentage; AD = apparent density (of soil); S% = sand percentage; L% = silt percentage; C% = clay percentage. EA = exchange acidity; CEC = cation exchange capacity; AS = acid saturation (%); SG = specific gravity; NTS = normal tangential shrinkage; NRS = normal radial shrinkage; NVS = normal volumetric shrinkage; GD = green density; MC= moisture content; Hw% = heartwood percentage; pith% = pith percentage; bark% = bark percentage. Variables in italics correspond to chemical elements.

Table 3 Multiple correlation analysis for the relationship between wood and soil properties of *Tectona grandis* plantations in Costa Rica

Wood property	Correlation parameters					
	1st	2nd	3rd	4th	5th	6th
SG**	*Cu***	Tree age**				
r = 0.460[a]	0.120[b]	0.087	–	–	–	–
NTS**	*P***	L%**	pH**			
r = 0.690	0.304	0.095	0.052	–	–	–
NRS**	*Fe***	L%**	AS**	*S%**	pH*	*P**
r = 0.833	0.404	0.151	0.043	0.036	0.036	0.029
Pith%**	Tree age**	*Ca***				
r = 0.562	0.167	0.149	–	–	–	–
Bark%*	dbh**	S%*				
r = 0.479	0.129	0.100	–	–	–	–
GD**	*Zn**					
r = 0.291	0.085	–	–	–	–	–
MC**	BA**	*Cu***				
r = 0.454	0.136	0.056	–	–	–	–
HP**	dbh **	PD*				
r = 0.609	0.306	0.065	–	–	–	–
PP**	Tree age**	*Ca***				
r = 0.562	0.167	0.149	–	–	–	–
BP*	dbh**	SP*				
r = 0.479	0.129	0.100	–	–	–	–

** Statistically significant at 99% confidence; * Statistically significant at 95% confidence; [a] Multiple correlation coefficient; [b] Contribution of the parameter to the coefficient of determination (r^2); S% = sand percentage; L% = silt percentage; AS = acid saturation (%); SG = specific gravity; NTS = normal tangential shrinkage; NRS = normal radial shrinkage; GD = green density; Pith% = pith percentage; Bark% = bark percentage; pH = pH of soil; dbh = diameter at breast height.
Variables in italics correspond to chemical soil elements.

shrinkage was highest on sites with silt content higher than 35% and phosphorus concentrations higher than 10 cmol(+)l^{-1} (Figure 2b). The lowest values of normal radial shrinkage were correlated with sites with silt contents lower than 20% and iron concentrations higher than 250 mg l^{-1}, while the highest values were obtained at silt contents higher than 35% and iron contents lower than 100 mg l^{-1} (Figure 2c).

The moisture content was found to be positively correlated with stand basal area and copper, obtaining the highest values at BA > 14 m^2 ha^{-1} and Cu > 16 mg l^{-1} (Figure 3a). The heartwood percentage was highest at dbh > 24 cm and stand densities of 300–600 trees ha^{-1}, although no significant correlations were found with any soil variables (Figure 3b). Plantations younger than 11 years of age on sites with calcium contents lower than 5 cmol(+)l^{-1} presented the highest pith proportions, while those plantations with the lowest values aged more than 12 years and contained over 25 cmol(+)l^{-1} of calcium (Figure 3c). Plantations with dbh > 24.0 cm and sand percentages < 30% showed the lowest bark contents (Figure 3d).

DISCUSSION

The cellular elements conforming the wood have their origin in the vascular cambial cells (Larson 1994). The physical and chemical soil properties are associated to cell division and differentiation of cambial cells, and this interaction is influenced as well by environmental or ecological conditions (Dünisch & Bauch 1994, Aguilar-Rodriguez *et al.* 2006).

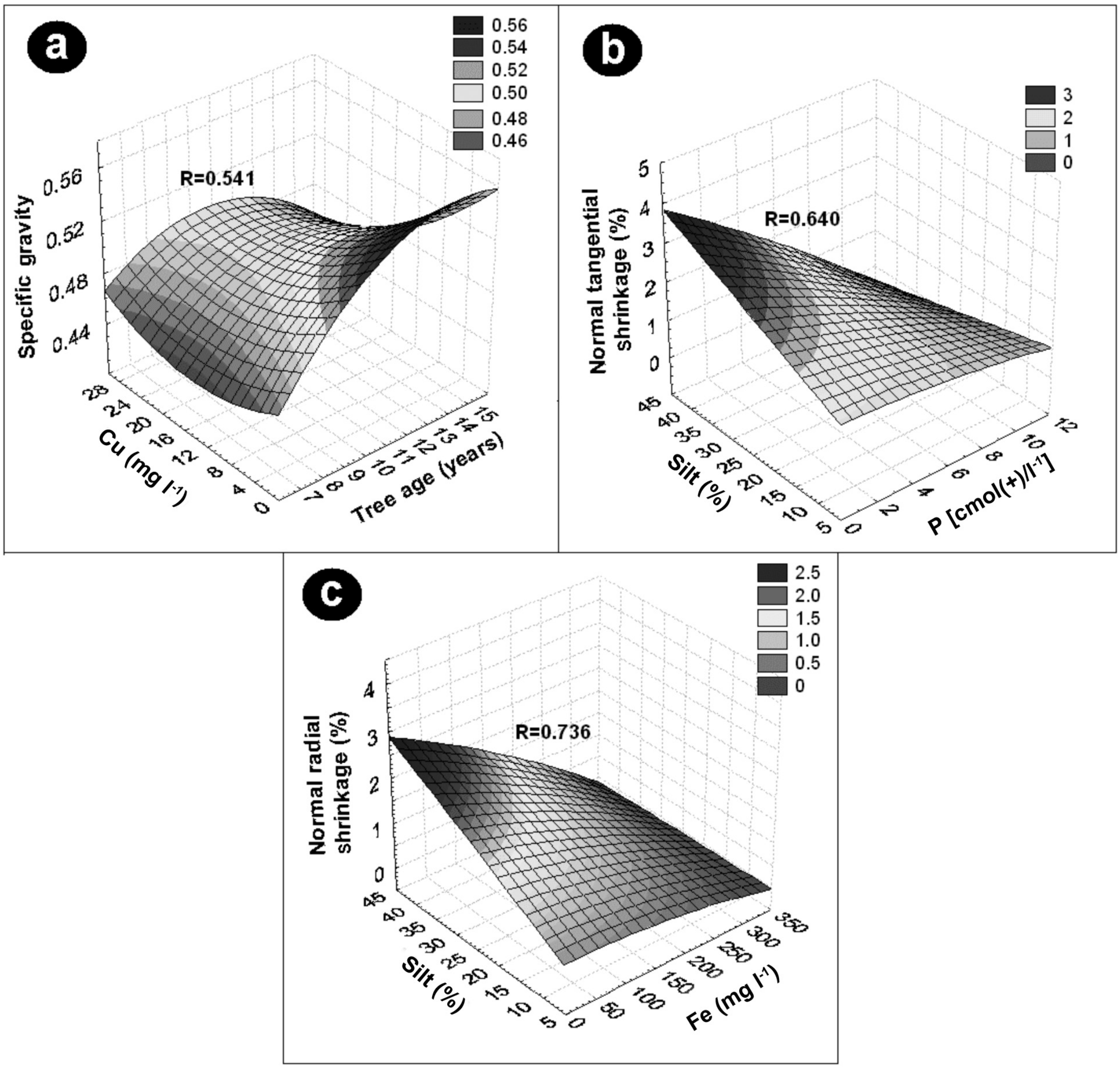

Figure 2 Response surfaces for the most significant variable correlations between wood and soil characteristics of *Tectona grandis* plantations in Costa Rica

Several scientific studies have reported relationship between cell elements and wood properties (Burgert *et al.* 2001). Recently, Badel and Perré (2007) found that tangential contraction can be predicted with 5% error by the distribution of the four woody anatomical elements (fibre, vessel, radial and axial parenchyma). Burgett *et al.* (2001) evaluated the influence of rays (quantity and frequency) on wood contractions. Similarly, Badel and Perré (2007) developed a model for predicting shrinkage/swelling and elastic properties of oak wood in transverse directions.

Few studies have reported the effect of site on the anatomic structure of wood on different cell elements such as fibres, vessels, rays and parenchyma. However, most of them omitted the relationship with physical or chemical soil components (Rao *et al.* 1966, Aguilar-Rodriguez *et al.* 2006). Soil properties were found to have significant relationship with wood shrinkage in the present study, as only the lime percentage and phosphorous content were related to the normal tangential shrinkage. This result is in concordance with a study carried out by Kadambi (1972) which states that teak trees require a certain silt percentage for a good physiological development.

Although in the present study, the effects of physical and chemical soil properties on the composition and distribution of cellular elements in teakwood were not determined, many studies have reported these effects. Rahman *et al.* (2005) found that the proportion and size of

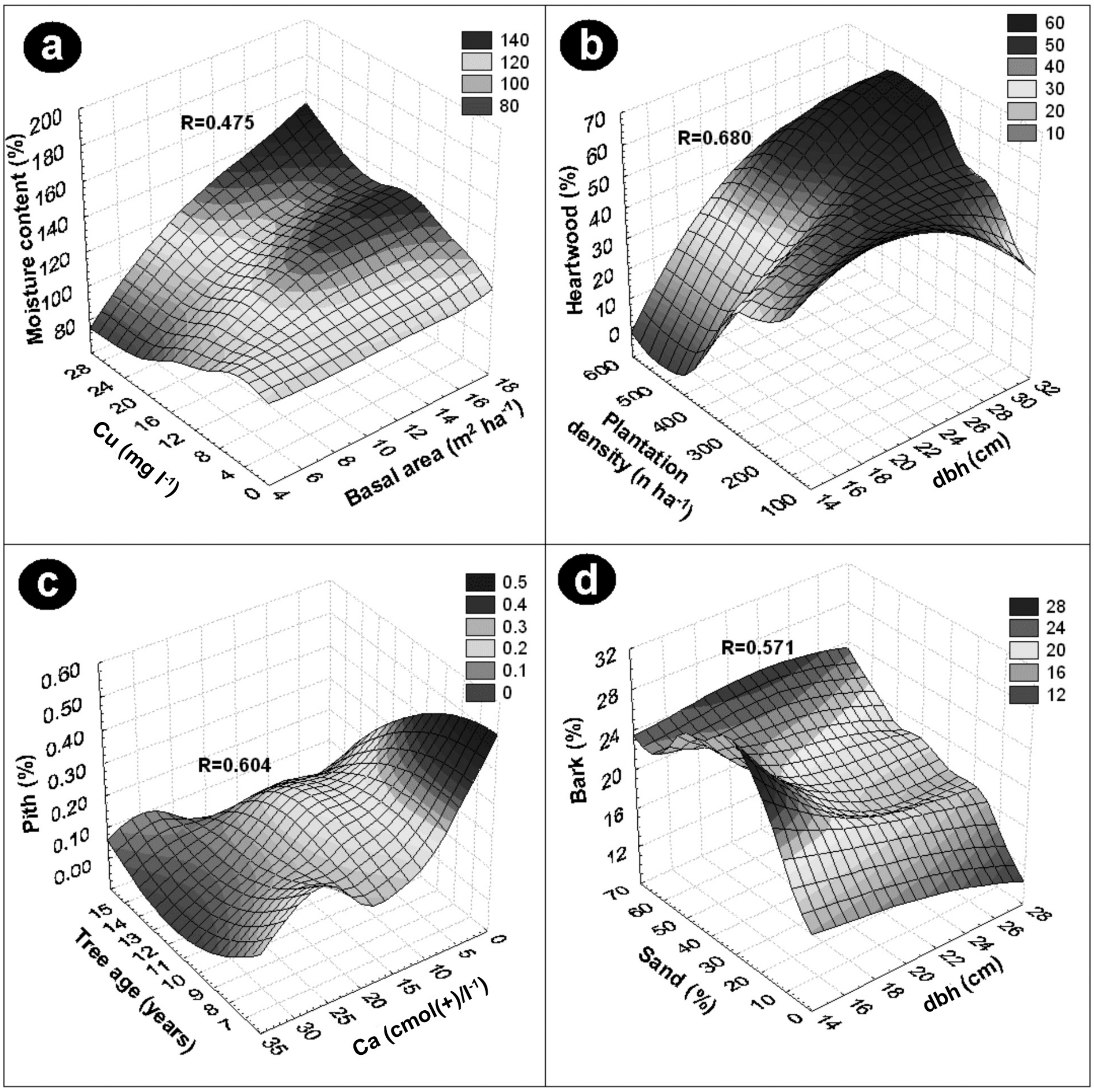

Figure 3 Response surfaces for the most significant variable correlations between wood and soil characteristics of *Tectona grandis* plantations in Costa Rica

rays differed between two sites with different soil fertility in Bangladesh, attributing the resistance levels of compression strength and wood density to the variation in ray proportion. Bhat and Priya (2004) attributed the weaker timber of north Kanara (India) provenance to its relatively high percentage of parenchyma and low percentage of fibres in the narrower rings, probably as an adaptation to nutrient-rich soil condition. Bhat *et al.* (2001) found that the juvenile period in teak was 15–25 years old based on regression analysis and visual interpretation of radial variation of certain anatomical properties. They concluded that growth rate and plantation site influence juvenile wood formation.

Although the phosphorous content in the soil has not been reported to have an effect on wood contractions, different studies carried out on forest plantations reported a positive effect of phosphorous on wood quality when incorporated into the soil via fertilization (Zobel & Van Bjuitenen 1989). Particularly, a higher growth rate has been reported for teak trees growing in Costa Rica when large contents of phosphorous are available in the soil (Alvarado 2006).

The mineral components have direct effects on vascular cambium. In the specific case of phosphorous, this element has the function of increasing cell division in the cambium, allowing better growth performance in plants. The increment in cambial activity is followed by modifications in the anatomical structure, mainly by pores of larger size, fibres with thinner cell walls and higher presence of parenchyma cells (Larson 1994). Therefore, such anatomical characteristics produce reduction in the normal tangential shrinkage.

Specific gravity of teak wood has been widely reported to increase with increasing tree age due to modifications in the anatomical structure during xylem formation in vascular cambium and by an increment in the thickness of the cell walls and a reduction in the frequency of vessels (Bhat *et al.* 2001, Moya *et al.* 2003, Perez & Kanninen 2003, Viquez & Perez 2005). The element copper significantly affected the specific gravity in the present study. However the stepwise regression analysis showed very poor influence of the element on this variable.

Other important structural tree components, such as bark and pith percentages were affected by growth variables, basal area and dbh, which can be manipulated to some extent by stand management regimes. The calcium content and sand percentage also presented a weak relationship with bark and pith percentages. Similarly, Akachuku and Abolarin (1989) found no differences in pith percentage among different sites for teak plantations in Nigeria.

Certain wood properties are affected exclusively by physical and chemical soil characteristics, such as wood contractions and green density. Other wood properties, such as specific gravity, moisture content, and bark and pith percentages can be partially explained by a combination of soil and plantation parameters. Heartwood content seems to be unaffected by any soil characteristic but rather dependent on age and plantation density, as reported previously for teak in Costa Rica by Perez and Kanninen (2003), Perez and Kanninen (2005b), and Viquez and Perez (2005).

Our results showed that some physical properties of teakwood were influenced by modification in the anatomical wood structure. These relationships can be interpreted as adaptations of tree growth to differences in physical and chemical soil properties, while other physical properties such as specific gravity and normal volumetric shrinkage should be attributed to other factors, such as genetic improvement. Consequently, it can be stated that soil characteristics have no significant influence on the main teak wood properties (wood density, heartwood percentage), and that a large range of soils in Costa Rica is suitable for teak wood plantations without detriment effect on important wood properties.

CONCLUSIONS

Soil characteristics (physical and chemical) had no important influence on teak wood properties. It can be stated that a large range of soils in Costa Rica is suitable for teak wood production, this in terms of achieving standard wood quality products. Certain soil characteristics, such as the content of calcium, copper and phosphorus, as well as sand and lime percentages, may be variables of interest for further studies as they showed interesting correlations with wood properties. The heartwood proportion, one of the most desired esthetic properties of teak wood, was least affected by site properties but was highly correlated with tree growth. Although site properties are not directly related to wood quality, a high yield of heartwood may be obtained on high productivity sites through intensive fertilization.

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