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

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Received April 2008

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Keywords: Bark; Heartwood; Pith; Specific gravity; Shrinkage; Wood quality.

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INTRODUCTION

Tectona grandis Linn F. has been largely planted on many tropical regions including Latin America, Asia, Africa, and Oceania, covering approximately 6 million hectares (FAO 2006). Teak plantations are being managed under new concepts orienting the fast growth and high productivity (Bermejo *et al.* 2004, Monteuuis & Goh 1999, 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 (Alvarado 2006, Nath *et al.* 2005, Pal & Huse 2006, Webb *et al.* 2006).

Teak wood is known in the international market by 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 the literature for different world regions (Bhat 1998, Bhat & Florence 2003, Perez & Kanninen 2003, Moya *et al.* 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.* 2002). A low wood density may be obtained on sites with favorable 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 report the relationship of wood production with physical and chemical characteristics of soils. Alvarado & Fallas (2004) and Ugalde *et al.* (2005) indicate 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 detail description of soil properties are 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, the Elastic Dynamic Module and the Moisture Content depend on the site location.

Few studies report the effect of chemical or physical soil characteristics on wood quality (Aguilar-Rodriguez *et al.*, 2006), as reviewed by Zobel and Van Buijtenen (1989) for other species different than teak. Recently, Dünisch & Bauch (1994) reported on the effect of water content and mineral nutrients of soil on the size of growth rings for *Picea abies*. Rigatto *et al.* (2002) found soil chemical properties affecting wood quality and physical properties affecting the production of cellulose in *Pinus tadea*, evidenced by the low wood density, short fiber, wide cellular wall, high contents of extractives and lignin, and low contents of cellulose. Yáñez *et al.* (2001) found that soil texture and water salinity were high correlated with anatomical characteristics of four species in a mangrove forest community in Mexico.

Mattson & Bergsten (2004) report a reduction in wood density by soil mechanization, as a response to more suitable conditions for a faster tree growth rate. Yañez *et al.* (2004) found that *Laguncularia racemosa* presented a high frequency of vessels, abundant parenchyma, and shorter fibers and vessels, related to sites with low salinity. Other fiber characteristics such as flexibility, rigidness, and Peteri & 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 effect 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, and covering a wide range of soil fertilities. The Northwest region reports an annual precipitation 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 between 2 800 and 5000 mm, an average annual temperature of 20-25 °C and with a short dry season in February and March.

Sample plantations

The 23 sampled plantations were property of 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 samples plots database previously established and continuously measured by the companies (Table 1).

Soil study

A soil profile of 1.0 x 1.0 x 1.0 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, the Water Retention Percentage, and the Water

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

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	N10°45’42”	W84°27’15”	25.80	25.60	264	13.59
2	14	N10°45’35”	W84°27’41”	16.90	16.90	226	5.07
3	14	N10°48’43”	W84°26’20”	22.10	25.30	264	13.27
4	14	N10°48’52”	W84°25’59”	15.50	16.30	245	5.11
5	7	N10°51’21”	W84°29’54”	18.07	19.90	396	12.32
6	7	N10°51’16”	W84°30’19”	14.89	15.34	377	6.97
7	14	N10°59’03”	W84°45’04”	19.10	22.30	188	7.34
8	14	N10°59’09”	W84°45’05”	18.10	25.40	151	7.65
9	9	N10°58’46”	W84°44’45”	16.13	19.37	318	9.37
10	11	N11°05’24”	W85°27’36”	17.70	21.30	300	10.69
11	11	N11°04’48”	W85°27’00”	15.90	18.90	440	12.34
12	10	N11°06’36”	W85°28’12”	18.00	22.50	440	17.49
13	10	N11°06’00”	W85°28’12”	15.00	18.90	520	14.59
14	8	N11°12’00”	W85°35’24”	13.10	17.80	580	14.43
15	8	N11°12’00”	W85°36’00”	16.50	21.10	500	17.48
16	10	N11°11’24”	W85°37’48”	14.10	18.70	460	12.63
17	10	N11°11’24”	W85°37’12”	19.10	25.10	320	15.83
18	15	N11°09’36”	W85°41’24”	22.50	26.50	300	16.55
19	15	N11°09’00”	W85°41’24”	21.60	24.20	320	14.72
20	13	N09°50’49”	W85°10’52”	23.20	25.40	172	8.70
21	13	N09°50’18”	W85°11’02”	23.30	27.40	160	9.40
22	15	N09°49’19”	W85°14’40”	22.00	23.20	328	13.90
23	15	N09°49’56”	W85°14’32”	22.10	24.20	338	15.50

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.

Texture analysis consisted on the determination of Clay, Limo, and Sand Content, Apparent Density, Water Retention Percentage, Water Useful Percentage, retention at 15 Bars, and retention at 0.33% Bars, according to the methodology of Forsythe (1985). The chemical analysis of the first soil layer was carried out using the methodologies of Briceño & Pacheco (1984), Bertsh (1986), and Diaz-Romeu & Hunter (1978), commonly implemented in Costa Rica for soil analyses.

Potassium chloride (KCl) was used as extracting media for the determination of the Exchangeable Acidity and the Calcium (Ca) and the Magnesium (Mg) content. A specter photometer of atomic absorption “Analisis 300” was implemented for determining the content of Phosphorus (P), Iron (Fe), Manganese (Mn), Cupper (Cu), Zinc (Zn), and Potassium (K). The Cation Exchange Capacity was measured by specter photometry of AA (CIA-SC09-01-02-2005) and the Acidity Saturation was determined by the Exchange Acidity.

Sample trees

A total of 3 average trees (with mean DBH, straight stem, normal branching, and without pests or diseases) were selected from the neighboring areas of each soil profile. North orientation was marked on each tree prior harvesting. A stem cross-sectional disk was taken at breast height (1.13 m) and place in plastic bags for further laboratory analysis.

The heartwood, bark, and pith percentages were determined on each stem disk. 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 (2003a). Properties include the radial, tangential, and volumetric shrinkage (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 disk (3.0 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% of relative humidity and 22 °C of temperature (air-dry condition) and the weight/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 hrs).

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 weight and divided by dry weight, both values expressed as percentages. The specific gravity was calculated as the oven-dry weight divided by volume in green condition (Basic), and air-dry 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 for further analysis. Selected variables for further comparison were Specific Gravity, Tangential, Radial and Volumetric Normal shrinkage, Green Density, Moisture Content, Heartwood, Bark, and Pith percentages. Next, variables were correlated with the physical and mechanical soil properties. Forward stepwise analysis was carried out for defining the priority soil variables affecting the 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. Wood shrinkage showed no correlation with specific gravity as reported by Bowyer et al. (2003), suggesting the influence of other variables not evaluated in the present study. Heartwood, bark, and pith percentages were not correlated with wood characteristics such as shrinkage, specific gravity, green density, or moisture content.

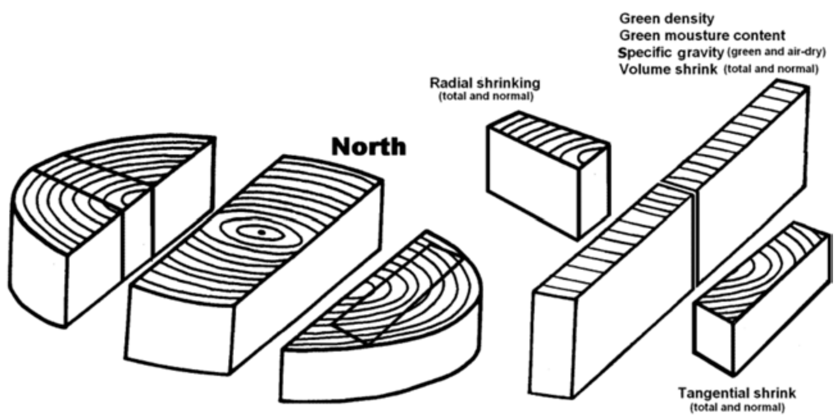

Figure 1 Sawing pattern use on each stem section for the analysis of mechanical wood properties

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 less correlated variables were Specific Gravity and Normal Volumetric Shrinkage (Table 2). Correlation coefficients were highly significant (α=0.05) but low (<0.64), probably influenced by the wide range of climatic and soil conditions in the studied plantations.

Wood properties were influenced by few physical and chemical soil properties, except for the Normal Radial Shrinkage which was correlated to six other variables (Table 3). Multiple correlation analysis showed that relationships between wood properties and soil characteristics were roughly explained by the different model parameters (r< 0.70).

The Phosphorus in the soil explained up to 30% of the Normal Tangential Shrinkage, complemented by the Limo content representing 9.5% of the total variation, while variations in Normal Radial Shrinkage were explained by Iron content (40%) and by Limo content (15.1%). Green Density was explained only in 8.5% by the Zink 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 to tree age (16.7%) and Calcium content (14.9%).

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

	Variable	Wood properties								
		SG	NTS	NRS	NVS	GD	MC	Hw%	Pith%	Bark%
Physical characteristics	D			0.300*		0.250*				
	ED		0.484**	0.520**					-0.237*	
	Ret33			-0.384**						0.288*
	Ret15					0.249*				
	WUP			-0.500**						0.288**
	AD		0.381**	0.460**						-0.255*
	S%			-0.304*						0.317**
	L%		0.465**	0.529**						
	C%									
Chemical characteristics	*pH*		0.370**	0.375**						
	EA								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			-0.276*					0.374**	
	P			-0.608**					0.366**	
	Zn					0.292*	0.334**			
	Cu	-0.280*					0.306*			
	Fe			-0.636**						
	Mn			-0.397**					0.289*	

Note: missing values correspond to no statistically significant values. **Legend:** ** Statistically significant at 99% confidence; * Statistically significant at 95% confidence. **(Soil physical characteristics)** 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%: Limo percentage; C%: Clay percentage. **(Soil chemical characteristics)** EA: Exchange acidity; CEC: Cation exchange capacity; AS: Acid saturation (%); variables in italic correspond to chemical elements. (**Wood properties)** 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.

Correlation parameters

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

Wood properties	Correlation parameters					
	1st	2nd	3rd	4th	5th	6th
SG**	Cu**	Tree age**				
r = 0.4601	0.1202	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	-	-	-	-

Legend: ** Statistically significant at 99% confidence; * Statistically significant at 95% confidence.[1] Multiple correlation coefficient; [2] Contribution of the parameter to the coefficient of determination (r^2); S%: Sand percentage; L%: Limo 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 italic correspond to chemical elements.

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 in response surfaces for ease of interpretation. The Wood Specific Gravity was highest in plantations older than 12 years and on sites with Cupper contents lower than 12 mg/kg (Figure 2a). The Normal Tangential Shrinkage was highest on sites with Limo content higher than 35%, Phosphorus concentrations higher than 10%, and Limo percentages lower than 20% (Figure 2b). The lowest values of Normal Radial Shrinkage were correlated to sites with Limo contents lower than 20% and Iron concentrations higher than 250 mg/kg, while the highest values where obtained at Limo contents higher than 35% and Iron contents lower than 100 mg/kg (Figure 2c).

The Moisture Content was found to be positively correlated with Stand Basal Area and Cupper, obtaining the highest values at BA > 14 m^2/ha and Cu > 16 mg/kg (Figure 3a). The Heartwood percentage was highest at DBH > 24.0 cm and Stand Densities of 300-600 trees/ha, although no significant correlations were found with any soil variables included in the present study (Figure 3b). Plantations younger than 11 years of age on sites with Calcium contents lower than 5% presented a the highest Pith proportions, while those plantations with the lowest values aged more than 12 years and contain over 25% 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 the 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).

Several scientific studies have reported a relationship between cell elements and wood properties (Burgert et al. 2001). Recently, Badel & Perré (2007) found that the tangential contraction can be predicted with 5% error by

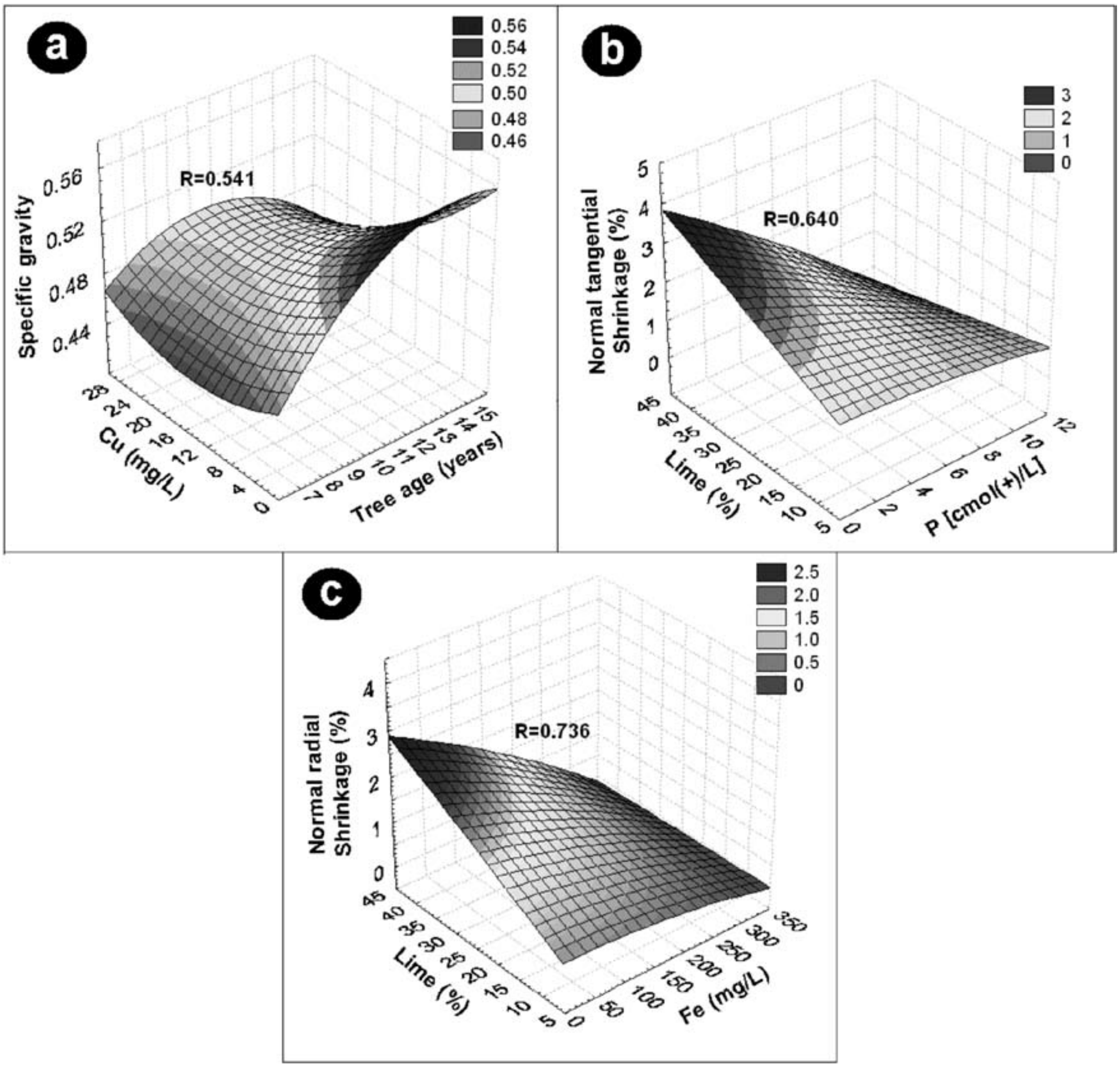

Figure 2 Response surfaces for the most significant variable correlations between wood and soil characteristics of *Tectona grandis* plantations in Costa Rica.

the distribution of the four woody anatomical elements (fibers, vessels, radial and axial parenchyma). Burget et al. (2001) evaluated the influence of rays (quantity and frequency) on the wood contractions. Similarly, Badel & Perré (2003) developed a model for predicting the shrinkage/swelling and the 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 fibers, vessels, rays, and parenchyma; however most of them omit the relationship with physical or chemical soil components (Rao *et al.* 1966, Aguilar-Rodriguez *et al.*, 2006). Soil properties were found to have a 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 Limo 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 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

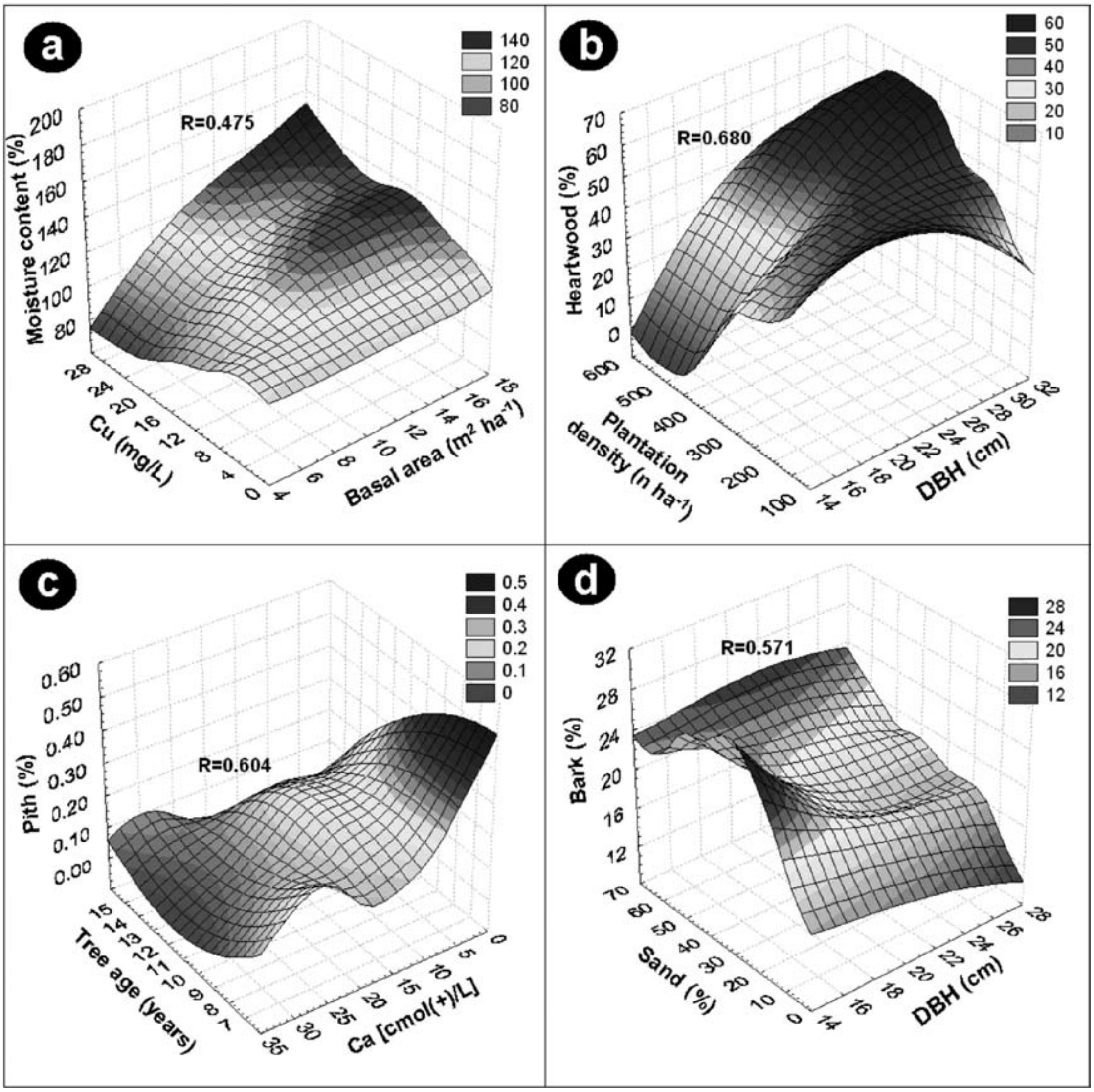

Figure 3 Response surfaces for the most significant variable correlations between wood and soil characteristics of *Tectona grandis* plantations in Costa Rica.

of fibers in the narrower rings, probably as an adaptation to nutrient-rich soil condition. Bhat *et al.* (2001) determined that juvenile period in teak was 15-25 years old based on segmented regression and visual interpretation of radial patterns in anatomical properties reveal and that the properties, growth rate and plantation site influenced on juvenile period.

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 report a positive effect of Phosphorous on wood quality when incorporated to the soil via fertilization (Zobel and 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 the vascular cambium. In the specific case of phosphorous, this element has the function of increasing the cell division in the cambium, allowing a better growth performance to the plants. The increment in cambial activity is followed by modifications in the anatomical structure, mainly by pores of larger size, fibers with thinner cell walls, and a higher presence of parenchyma cells (Larson, 1994). Therefore, such anatomical characteristics produce a 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 anatomic 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 Cupper affected significantly the specific gravity in the present study; however the stepwise regression analysis showed a very poor influence of the element on this variable.

Other important structural tree components, such as bark and pith percentages, were affected by the growth variables Basal Area and DBH, which can be manipulated to some extent by stand management regimes. The Calcium content and sand percentage presented also a weak relationship with bark and pith percentages. Similar to this, Akachuku & 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 dependant of age and plantation density, as reported previously for teak in Costa Rica by Perez & Kanninen (2003), Perez & Kanninen (2005b), and Viquez & Perez (2005).

According with ours results, 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 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 main teak wood properties (Wood Density and Heartwood Percentage), and that a large range of soils in Costa Rica are suitable for teak wood plantations without a detriment on important wood properties.

CONCLUSIONS

1. The most important conclusion of the present study is that the soil characteristics (physical and chemical) have no important influence on teak wood properties. Consequently, it can be preliminarily stated that a large range of soils in Costa Rica are suitable for teak wood production, this in terms of achieving standard wood quality products.
2. Certain soil characteristics, such as the content of Calcium, Cupper, and Phosphorus, as well as the Sand and Lime percentages, may be variables of interest for further studies as they showed slight but interesting correlations with wood properties in the present study.
3. The heartwood proportion, one of the most desired esthetic properties of teak wood, is less affected by site properties but is highly correlated to tree growth. Consequently, 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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