Ann. For. Sci. 67 (2010) 109
© INRA, EDP Sciences, 2009
DOI: 10.1051/forest/2009088

Available online at:
www.afs-journal.org

Original article

Wood colour variation in sapwood and heartwood of young trees of *Tectona grandis* and its relationship with plantation characteristics, site, and decay resistance

Róger Moya*, Alexander Berrocal

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

(Received 8 January 2009; revised version 25 February 2009; accepted 2 July 2009)

Keywords:
CIELab colour system /
tropical wood /
***Tectona grandis* /**
sapwood /
hardwood /
management plantation

Abstract

• Wood colour of *Tectona grandis* produced from fast-growth plantations is highly variable and the causes of this variation are relatively unknown.
• With the purpose of understanding the colour variation, different fast-growth plantations were sampled with different growth rates, tree ages, and sites.
• Wood colour was measured with a CIELab system, where three variables are estimated: coordinate L^* for lightness, coordinate a^* defines redness and coordinate b^* defines yellowness.
• Results showed only a negative correlation between L^* and a^*. L^* and a^* were negatively and positively respectively correlated with pith distance in heartwood, but not for b^*. No correlations were found between L^* and b^* in sapwood and plantation characteristics, while a^* was positively correlated with age and height of tree and growth rate. In heartwood, tree age and diameter at breast height were correlated with all colour parameters, but tree height and plantation density were correlated with a^* and b^*. Cluster site had correlation with L^*. Multiple correlation analysis showed that the heartwood is increasing darker (L^*) and redder (a^*) when the trees are older and bigger. Correlation coefficient shown that sapwood and heartwood with lighter colour (L^*) is less resistance to fungal attack, but redness colour (a^*) increasing decay resistance.

Mots-clés :
CIELab /
bois tropicaux /
***Tectona grandis* /**
aubier /
bois de cœur /
plantations

Résumé – Les variations de couleur dans l'aubier et le duramen de jeunes arbres de *Tectona grandis*, en relation avec les caractéristiques des plantations, du site et de la durabilité.

• Il y a une grande variabilité de la couleur du bois de *Tectona grandis* produit à partir de plantations à croissance rapide et les causes de ces variations sont relativement inconnues.
• Pour comprendre l'origine des variations de couleur nous avons échantillonné dans des plantations à croissance rapide qui diffèrent entre elles en termes de vitesse de croissance, d'âge et de site.
• La couleur du bois a été mesurée avec le système CIELab qui permet la mesure de trois variables colorimétriques : la luminance L^* allant du noir au blanc, a^* et b^* allant respectivement du vert au rouge et du bleu au jaune.
• Les résultats montrent une corrélation négative entre L^* et a^*. Dans le bois le cœur il y a une corrélation négative entre L^* et la distance à la moelle et une corrélation positive entre a^* et la distance à la moelle : aucune corrélation n'apparaît pour b^*. Dans l'aubier, on ne trouve aucune corrélation entre L^* et b^* et les caractéristiques des plantations. Cependant a^* est corrélé positivement avec l'âge, la hauteur et la vitesse de croissance des arbres. Dans le bois de cœur, l'âge et le diamètre à 1,3 m des arbres sont corrélés avec les trois coordonnées chromatiques mais la hauteur des arbres et la densité de plantation sont corrélées avec a^* et b^*. Il y a une corrélation entre le site et L^*. On montre que le bois de cœur est d'autant plus sombre et rouge que les arbres sont plus vieux et plus gros. Les corrélations obtenues montrent que les bois d'aubier et de cœur qui sont les plus clairs résistent moins bien aux attaques fongiques et que les bois de tendance plus rougeâtre ont une meilleure résistance aux pourritures.

* Corresponding author: rmoya@itcr.ac.cr

Article published by EDP Sciences

1. INTRODUCTION

Wood colour, which differs widely among species as well as within a single tree (Liu et al., 2005; Nishino et al., 1998), is an important factor for determining specific uses such as furniture and decorative veneers, both very important marketing attributes (Mazet and Janin, 1990). One of the most accurate and commonly used systems for measuring wood colour is the CIELab colour system.

It has been used to measure colour variation and its relation to plant genetic sources (Sotela et al., 2008), effect of drying on colour (Möttönen et al., 2002), relationship between colour and decay resistance (Gierlinger at al., 2004), and effect of thermal treatment on wood colour (Johansson and Morén, 2006).

Tectona grandis L.f. has been widely planted in all tropical regions including Latin America, Asia, Africa, and Oceania, in total covering approximately 6 million hectares (FAO, 2006). Teak is a premier hardwood valued for its durability, aesthetics, and its golden brown colour (Thulasidas et al., 2006). According to Bhat (1999), there are four colour groups for *T. grandis* wood from native areas: (i) uniform golden yellowbrown (typical) (ii) a darker yellowbrown (iii) uniform grey-brown (produced from trees that grow no larger than the pole stage) and (iv) light uniform yellow. Short-rotation trees growing in forest plantations generally fetch a lower price in the timber market because the wood is of inferior quality in such attributes as colour, density, and mechanical properties (Thulasidas et al., 2006).

In Costa Rica, large teak plantations have been established and managed for fast growth and high timber productivity (Pérez and Kanninen, 2005), with trees felled in a rotation period of less than 20 y. The wood from these trees is usually light brown with a large variation in colour. This results in a reduced market value, and has led to its nickname "baby teak wood".

Bhat et al. (2005), Thulasidas et al. (2006) and Lukmandaru and Takahashi (2008) report on the effects of tree age on teak wood colour variation and its relationship to tree age and decay resistance. However, wood colour is influenced by many other factors, including site, stand conditions and management, genetic source and age (Phelps et al., 1983). Most studies focused on heartwood with little consideration given to sapwood, although several studies of fast-grown *T. grandis* trees have shown that a high sapwood fraction is present. Pérez and Kanninen (2003) indicated that sapwood can reach 45% of the total wood volume at 30 y, and is even greater in young trees. Bhat (2000) also reported that young trees have a high proportion of sapwood, with low natural durability.

To understand colour variation of fast-growing *T. grandis*, we studied trees from three sites in Costa Rica, having different growth rates and ages. We investigated the influence of growth rate, age, diameter at breast height (DBH), height, site characteristics, and location of boards relative to the pith on wood colour parameters of sapwood and heartwood. The relationship between wood colour and decay resistance was studied to examine the possibility of using colour as a parameter for quality control.

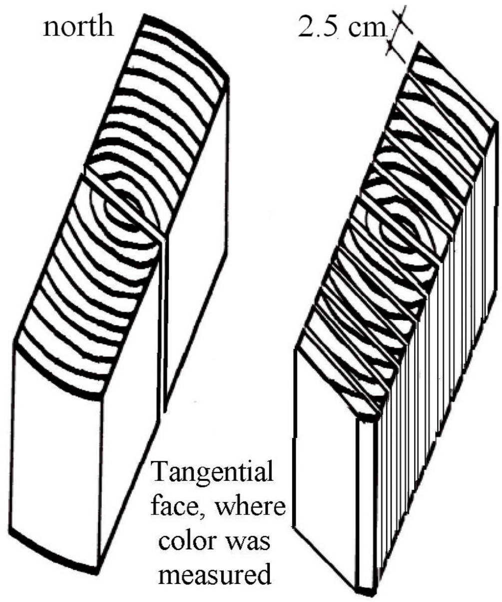

Figure 1. Sawing pattern use for each stem section to obtain specimens for wood colour.

2. MATERIALS AND METHODS

2.1. Study area and sample plantations

A total of 23 plantations of 7 to 15 y were selected in the north and northwest regions of Costa Rica covering three cluster sites (Tab. I). Annual precipitation was between 1 500 and 5 000 mm, with an average annual temperature of 20–28 °C. There was a long dry season between January and April in the northwest regions of clusters 2 and 3 and a short dry season in February and March in north regions of cluster 1. The 23 sampled plantations were established by three different private companies along the study area. Stand density varied between 160 to 580 trees/ha, depending on plantation age, management, and site conditions (Tab. I). Plantation conditions were detailed previously in Table I in Moya and Pérez (2008).

2.2. Sampled trees and wood sample preparation

Three trees from each plot were selected, taking into consideration mean DBH, stem straightness, normality of branching, and absence of pests or diseases. The north side was marked on each tree prior to harvesting. One 40-cm long log was cut at breast height from each tree. These were stored in plastic bags until laboratory analysis. A 3-cm-wide board was sawn through the pith in the north to south direction from each log (Fig. 1). These boards were conditioned at 22 °C and 60% relative humidity for several weeks until reaching a moisture content of 11–12%. The boards were then sawn into 2.5 cm wide strips, with each strip labelled to indicate its radial position in the stem (i.e., its relative distance from the pith) and whether it consisted of sapwood or heartwood. Tangential surfaces were sanded to reduce the effects of surface variation on colour, and after 20 h the wood colour was measured.

Table I. Average dendrometric variables and site locations of each plantation evaluated in the present study.

Clusters	Site code	Age (years)	Latitude (N)	Longitude (W)	Tree height (m)	Diameter breast height level (cm)	Stand density (trees ha^{-1})
1	1	14	N10° 45′ 42″	W84° 27′ 15″	25.80	25.60	264
	2	14	N10° 45′ 35″	W84° 27′ 41″	16.90	16.90	226
	3	14	N10° 48′ 43″	W84° 26′ 20″	22.10	25.30	264
	4	14	N10° 48′ 52″	W84° 25′ 59″	15.50	16.30	245
	5	7	N10° 51′ 21″	W84° 29′ 54″	18.07	19.90	396
	6	7	N10° 51′ 16″	W84° 30′ 19″	14.89	15.34	377
2	7	14	N10° 59′ 03″	W84° 45′ 04″	19.10	22.30	188
	8	14	N10° 59′ 09″	W84° 45′ 05″	18.10	25.40	151
	9	9	N10° 58′ 46″	W84° 44′ 45″	16.13	19.37	318
3	10	11	N11° 05′ 24″	W85° 27′ 36″	17.70	21.30	300
	11	11	N11° 04′ 48″	W85° 27′ 00″	15.90	18.90	440
	12	10	N11° 06′ 36″	W85° 28′ 12″	18.00	22.50	440
	13	10	N11° 06′ 00″	W85° 28′ 12″	15.00	18.90	520
4	14	8	N11° 12′ 00″	W85° 35′ 24″	13.10	17.80	580
	15	8	N11° 12′ 00″	W85° 36′ 00″	16.50	21.10	500
	16	10	N11° 11′ 24″	W85° 37′ 48″	14.10	18.70	460
	17	10	N11° 11′ 24″	W85° 37′ 12″	19.10	25.10	320
	18	15	N11° 09′ 36″	W85° 41′ 24″	22.50	26.50	300
	19	15	N11° 09′ 00″	W85° 41′ 24″	21.60	24.20	320
5	20	13	N09° 50′ 49″	W85° 10′ 52″	23.20	25.40	172
	21	13	N09° 50′ 18″	W85° 11′ 02″	23.30	27.40	160
	22	15	N09° 49′ 19″	W85° 14′ 40″	22.00	23.20	328
	23	15	N09° 49′ 56″	W85° 14′ 32″	22.10	24.20	338

2.3. Colour measurement

Wood colour was measured using a portable Miniscan XE plus colorimeter (HUNTER LAB) at ambient temperature and humidity. The colorimeter was recalibrated each time it was used, using a white standard probe supplied by HUNTER LAB. The reflectance spectra were recorded using the standardized CIEL$^*a^*b^*$ chromaticity system as a function of wavelength (BYK-Gardner, 2004). The measurement was within the visible range of 400–700 nm at intervals of 10 nm with a measuring aperture of 11 mm. For reflection readings, the observer component was set at an angle of 90° to the surface of the specimen. The standard illuminant D65 (corresponding to daylight at 6 500 K) was used as the colour space measuring and computing parameter. The CIEL$^*a^*b^*$ colour system estimates the value of three variables: coordinate L^* for lightness, representing the position on the black-white axis ($L^* = 0$ for black, $L^* = 100$ for white); coordinate a^* for the position on the red-green axis (positive values for red, negative values for green); and coordinate b^* for the position on the yellow-blue axis (positive values for yellow, negative values for blue) (Hunterlab 1995). Three measurements along the tangential face were taken from each wood sample (Fig. 1) and average values were obtained for L^*, a^* and b^*. A total of 394 samples were measured; 267 samples were heartwood and 127 were sapwood.

2.4. Decay resistance

Decay resistance specimens measuring 2.5×2.5×2.5 cm were cut from the same locations where wood colour was measured (267 samples for heartwood, 127 samples for sapwood). The white-rot fungi *Trametes versicolor* L. Fr. and *Pycnoporus sanguineus* (L.) Merrill were used for testing natural decay resistance following ASTM Standard D-2017-81 (ASTM, 2003). The relative resistance of each test block to decay was measured as the percentage loss in oven-dry weight during a 16-week exposure to the fungi. Although ASTM D-2017-81 specifies that sample dimensions are 2.5 × 2.5 × 0.9 cm, we modified the procedure to use 2.5 × 2.5 × 2.5 cm samples.

2.5. Statistical analysis

The normality and the presence of outliers were examined for each colour parameter. Regression analysis was used to determine the relationships of colour coordinates ($L^*a^*b^*$) in sapwood and heartwood, and the effects of pith distance and decay resistance on colour variation. Pearson correlation coefficients were computed to show the relationships among colour coordinates and plantation characteristics (site, growth rate, age and height of tree, and DBH). Finally, we used forward stepwise regression to determine the plantation variables having the greatest effects on wood colour. The colour coordinates of all boards in each tree were averaged and used to compute the correlation coefficients among colour and with plantation variables. SAS (SAS Institute Inc.) and STATISTICA 6.0 (Statsoft Inc.) programs were used for the statistical computations.

3. RESULTS AND DISCUSSION

3.1. Wood colour

Table II shows the average colorimetry results for sapwood and heartwood of *T. grandis* in CIEL$^*a^*b^*$ colour systems. Note that the values of colour coordinates are positive. All objects can have their colour described by the three variables L^*,

Table II. Colour parameters of *Tectona grandis* growing in Costa Rica with CIELab system.

Wood	L^* (lightness)	a^* (redness)	b^* (yellowness)
Sapwood	73.8	5.8	25.22
(N = 127)	[63.62–80.90]	[1.66–11.65]	[19.44–32.62]
	(3.45–4.66)	(1.84–33.28)	(2.95–11.70)
Heartwood	58.15	10.4	25.91
(N = 267)	[46.78–76.56]	[7.07–13.56]	[20.06–30.11]
	(5.66–9.67)	(1.30–12.35)	(2.21–8.54)

The values in square parenthesis represent minimum and maximum values and normal parenthesis standard deviations and variation coefficients.

a^* and b^* as described in the Materials and Methods. That is, the colour composition of *T. grandis* wood can be described using the combination of different tonalities of lightness, redness, and yellowness. The values of L^* and b^* in the sapwood and L^*, a^* and b^* in the heartwood were only small portions of the possible ranges and had coefficients of variability (CV) of less than 12.35% (Tab. II).

The lightness index (L^*) ranged from 63.62 to 80.90 in sapwood and from 46.78 to 75.56 in heartwood. The redness index (a^*) ranged from 1.66 to 11.65 and 7.07 to 13.56 for sapwood and heartwood, respectively; and yellowness (b^*) from 19.44 to 32.62 and from 20.06 to 30.11 in the heartwood and sapwood, respectively (Tab. II). The variation of extractives or chemical composition of lignin produced from different soil properties can explain the wood colour variation of heartwood. For example, redness (a^*) and lightness (L^*) are correlated with extractive content, while yellowness is primarily related to the photochemistry of the major wood components, especially lignin (Gierlinger et al., 2004).

In sapwood, the a^* values had the greatest variability compared with the possible range, with a CV of 33.28% (Tab. II). As expected, the colour composition of heartwood and sapwood are different. Heartwood colour has lower values of L^* and higher values of a^* compared to sapwood (Tab. II). The change in colour from sapwood to heartwood is due to the synthesis and accumulation of extractives during heartwood formation. Variation in colour within heartwood is due to oxidation and polymerization reactions that take place as wood ages (Gierlinger et al., 2004).

The wood colour variation that we found in *T. grandis* is considered large for end users (Bhat, 1999). The variation in the colour space of a three-dimensional model is the quadratic summation of differences in each coordinate (Gonnet, 1993). Mazet and Janin (1990) report that oak veneer samples evaluated by 90 French and Italian assessors from woodworking industries consider that a difference of over two units in the value of $[(L^* - L^*)^2 + (a^* - a^*)^2 + (b^* - b^*)^2]$ is distinguishable to the human eye. For agricultural or horticultural applications this difference varied from 1.0 to 3.0 (Voss and Hale, 1998). Therefore, a difference in two points in different samples of *T. grandis* in all coordinates of colour systems will produce a difference distinguishable to the human eye.

The L^*, a^*, and b^* values obtained in wood from fast-growth plantation *T. grandis* in Costa Rica are different from the results found in other studies. For example, Thulasidas et al. (2006) reported average values of 56.34, 6.85, and 23.44 for L^*, a^*, and b^*, respectively, for heartwood from trees growing in plantations in India. The *T. grandis* heartwood from trees growing in Costa Rican is lighter and redder than wood from India (Tab. II). However, this comparison must be interpreted with caution because genetic factors, tree age, climate and soil fertility are different for India and Costa Rica, and different colour equipment was used in each study. Our study used a colorimeter, whereas Thulasidas et al. (2006) used a UV spectrophotometer, so equipment differences may be responsible for the differences in wood colour determination. Lukmandaru and Takahashi (2008) studied *T. grandis* trees of different ages on Java, and found ranges wider than ours. L^* ranged from 75–77 and 54–60, for sapwood and heartwood, respectively, a^* ranged from 2–3 and 4–6 in sapwood and heartwood, respectively, and b^* ranged from 22–25 and 24–26 in sapwood and heartwood, respectively. These ranges are narrower than those for Costa Rican *T. grandis* (Tab. II).

3.2. Relation between wood colour coordinates

Figure 2 shows the relationships among the colour parameters defining the heartwood and sapwood measurements. A significant correlation was found only between L^* and a^* in both sapwood and heartwood. A low coefficient of determination was found in both, R^2 = 0.38 for heartwood and R^2 = 0.43 for sapwood (Fig. 2a). No significant correlation was found between L^* and b^* (Fig. 2b) and b^* and a^* (Fig. 2c). These results show that the variation in wood colour of *T. grandis* is produced by an inverse variation between L^* and a^* coordinates, lightness and redness, respectively. Nishino et al. (1998) measured the correlations between different colour parameters of many tropical species from Guiana, and their results agree with our findings for *T. grandis*. They found significant relationships between L^* and a^*, but not between a^* and b^*. In *Fagus sylvatica*, Liu et al. (2005) found that the parameters of the CIE$L^*a^*b^*$ colour system were significantly correlated (L^* with a^*, L^* with b^*, and a^* with b^*), but in *T. grandis* the only significant correlation was with a^*.

3.3. Wood colour variation with distance from the pith

The colour coordinates L^* and a^* were statistically correlated (α = 0.05) with distance from pith for heartwood, but not for sapwood (Fig. 3). However, low but significant correlation coefficients were found in heartwood, (R = −0.36) for the relationships of L^* with distance from pith (Fig. 3a) and a^* with distance from pith (R = 0.36) (Fig. 3b). For coordinate b^*, no significant correlations were found (Fig. 3c). In summary, the heartwood colour is lightest with lowest redness near the pith, becoming darker with increase in redness as distance from pith increases.

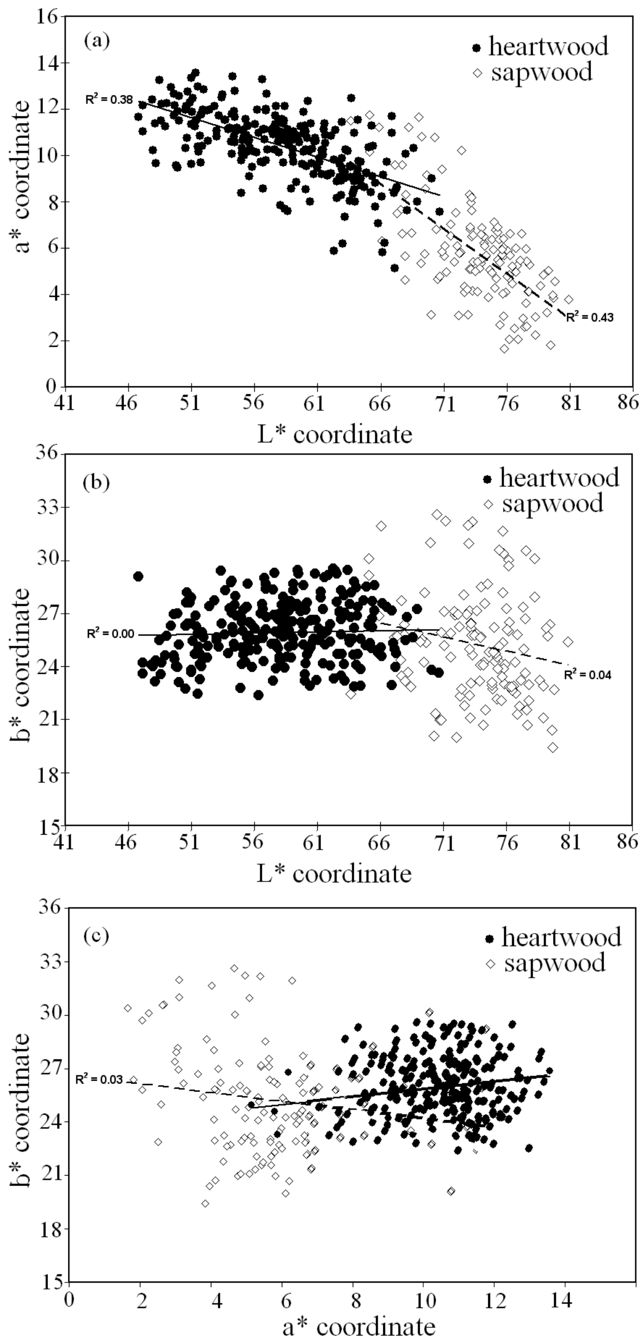

Figure 2. Relationship between L^* vs. a^* (a), L^* vs. b^* (b) and a^* vs. b^* (c) for *Tectona grandis*, separating heartwood and sapwood (N sapwood = 127 and N heartwood = 267).

Figure 3d shows the relative reflectance according pith distance for a tree sampled. The heartwood near the pith has higher values of reflectance than others radial position in different wavelength. Meanwhile, the reflectance decreases with increase the distance of pith. On the others hand, the highest relative reflectance in the sapwood occurred from 400 to 500, but peak was presented almost 500 nm (Fig. 3c). Kokutse et al. (2006) and Bhat et al. (2005) with teak trees grown in Togo and India, respectively, in fast-growth plantations agreed with the wood colour variation found for teak trees growing in Costa Rican plantations, in colour variation with pith distance for L^* and a^* parameters for CIELAB colour systems, and no significant difference in b^* colour parameters.

3.4. Wood colour variation with plantation characteristics

In sapwood, no significant correlations were found between L^* and b^* and plantation characteristics, while a^* was highly correlated ($P < 0.01$) with tree age and growth rate. Low correlation ($P < 0.05$) was found between a^* and tree height and plantation density (Tab. III). Redness index (a^*) increases with age and height of the tree. Also, decreasing growth rate and plantation density increases redness value. In heartwood, tree age and DBH were highly correlated with all colour parameters, except for b^* with tree age, which had a low correlation. There were negative correlations between lightness index (L^*) and tree age and DBH, and positive correlations between redness and yellowness and tree age and DBH (Tab. III). The a^* and b^* coordinates were not significantly correlated with tree height and plantation density, but L^* was correlated significantly with a^* and b^* (negatively and positively, respectively) (Tab. III). Growth rate correlated significantly with L^* and a^* (positively and negatively, respectively) but no significant correlation was found with b^*. The cluster sites were independent variables with less effect on wood colour parameters. There was a strong correlation between this variable and yellowness index (Tab. III). Thulasidas et al. (2006) agreed with our results. They measured the heartwood colour variation of home garden *T. grandis* trees from wet and dry localities of Kerala (India) and found that only the yellowness index (b^*) was different between dry and wet localities and no significant difference was observed among localities with regards to redness (a^*) and lightness (L^*). These results probably indicate that the yellow coordinate of *T. grandis* colour is more affected by soil type or fertility and climate conditions, but it is necessary to confirm this.

All plantation characteristics significantly affected colour parameters, and it was determined that there are strong relationships among all characteristics. No correlation was found between cluster sites and plantation characteristics. Tree age and growth rate were the most correlated variables (Tab. IV). This means that wood colour is produced by a combination of the plantation characteristics. Multiple correlation analysis showed that the relationships between wood colour parameters and plantation characteristics were roughly explained by the different model parameters, and that tree age was the main plantation characteristic that determines redness and lightness index of wood colour of *T. grandis*, but cluster sites affected mainly the yellowness index (b^*) of heartwood. DBH affected the coordinates of wood colour in heartwood, having the greatest effect in lightness index (10.1%). Growth rate affected only a^* coordinates in heartwood (Tab. IV).

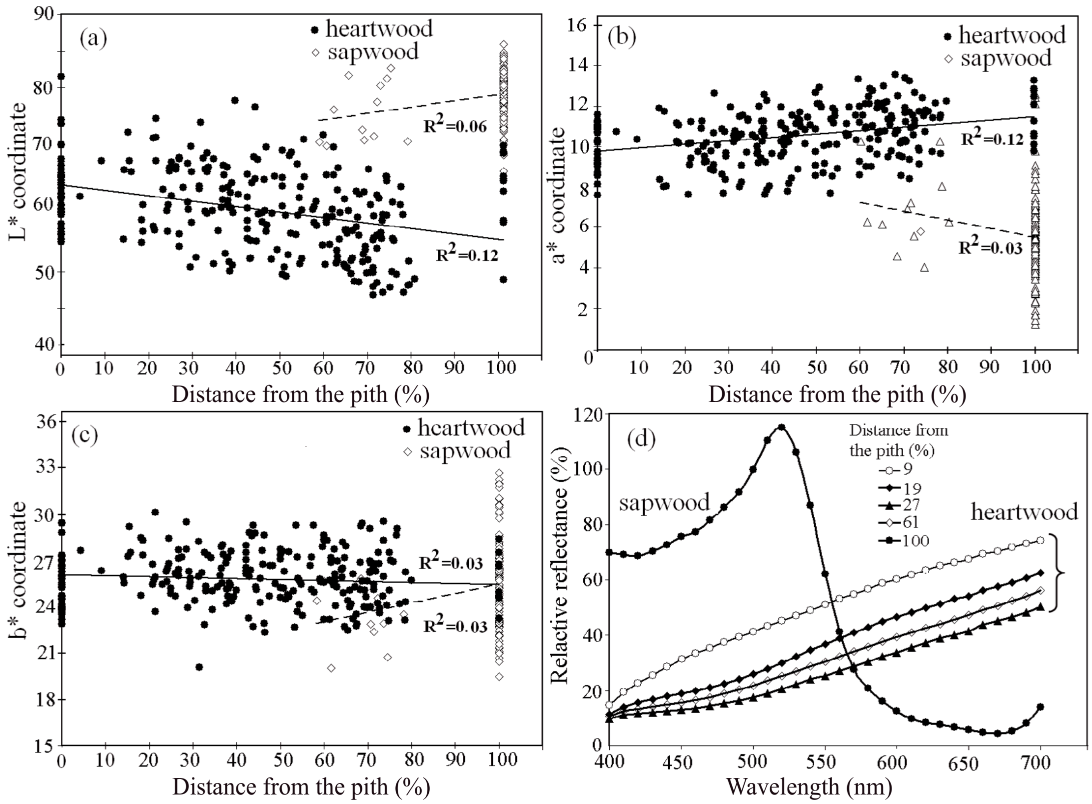

Figure 3. Relationship between distance from the pith and L^*, a^*, b^* (a, b, c) and relative reflectance (d) for heartwood and sapwood of *Tectona grandis* (N sapwood = 127 and N heartwood = 267).

Table III. Pearson correlation coefficients for the relationship between colour parameters and plantation characteristics of *Tectona grandis* in Costa Rica.

Plantation characteristics	CIELab parameters in sapwood (*N* = 127)			CIELab parameters in heartwood (*N* = 267)		
	L^*	a^*	b^*	L^*	a^*	b^*
Tree age	-0.13^{ns}	0.38**	0.09^{ns}	–0.55**	0.42**	0.26*
Tree height	-0.09^{ns}	0.31*	-0.08^{ns}	–0.28*	0.20^{ns}	0.31^{ns}
DBH	-0.00^{ns}	0.14^{ns}	-0.04^{ns}	–0.40**	0.38**	0.38**
Growth rate	0.15^{ns}	–0.38**	-0.16^{ns}	0.41**	–0.30*	-0.06^{ns}
Plantation density	0.05^{ns}	–0.33*	-0.09^{ns}	0.30*	-0.22^{ns}	0.20^{ns}
Cluster	-0.23^{ns}	0.18^{ns}	-0.15^{ns}	-0.09^{ns}	0.16^{ns}	0.84**

** Statistically significant at 99% confidence level; * statistically significant at 95% confidence level, ^{ns} not significantly different, DBH: diameter at breast height.

Table IV. Pearson correlation coefficients for the relationship among sampled plantation characteristics of *Tectona grandis* in Costa Rica (*N* = 69).

Plantation characteristics	Tree age	Tree height	DBH	Growth rate	Plantation density	Cluster
Tree age	1					
Tree height	0.67**	1				
DBH	0.56*	0.85**	1			
Growth rate	–0.80**	-0.18^{ns}	0.02^{ns}	1		
Plantation density	–0.66**	–0.55*	–0.45*	0.45*	1	
Cluster	0.18^{ns}	0.25^{ns}	0.32^{ns}	-0.02^{ns}	0.24^{ns}	1

** Statistically significant at 99% confidence level; * statistically significant at 95% confidence level, ^{ns} not significantly different.

Table V. Multiple correlation analysis for the relationship between heartwood colour and plantation characteristics of *Tectona grandis* in Costa Rica (N = 267).

Wood properties	Multiple determination coefficient		
	1st	2nd	3rd
Redness index (a^*) sapwood	Tree age**	–	–
r = 0.387[1]	0.15		
Lightness index (L^*)	Tree age**	DBH**	–
r = 0.649	0.304[2]	0.101	–
Redness index (a^*)	Tree age**	Growth rate**	DBH**
r = 0.547	0.176	0.093	0.030
Yellowness index (b^*)	Cluster**	DBH**	–
r = 0.844	0.698	0.014	

** Statistically significant at 99% confidence level; * statistically significant at 95% confidence level. [1] Multiple correlation coefficient; [2] contribution of the parameter to the coefficient of determination (r^2).

Table VI. Pearson correlation coefficients for the relationship between colour parameters and decay resistance of *Tectona grandis* in Costa Rica.

Type of wood	Colour coordinates	*Trametes versicolor*	*Pycnoporus sanguineous*
All samples: sapwood	L^*	0.66**	0.64**
and heartwood	a^*	–0.65**	–0.62**
(N = 394)	b^*	0.10^{ns}	0.07^{ns}
Sapwood	L^*	0.43*	0.16^{ns}
(N = 127)	a^*	–0.62**	–0.32*
	b^*	0.19^{ns}	0.08^{ns}
Heartwood	L^*	0.55**	0.47*
(N = 267)	a^*	–0.44*	–0.33*
	b^*	0.07^{ns}	0.07^{ns}

** Statistically significant at 99% confidence level; * statistically significant at 95% confidence level, ^{ns} not significantly different.

All plantation characteristics significantly affected colour parameters, and it was determined that there are strong relationships among all variables, but no correlation was found between cluster sites and plantation characteristics. Tree age and growth rate were the most highly correlated variables (Tab. IV). This means that wood colour is produced by a combination of the plantation characteristics. Multiple correlation analysis showed that relationships between wood colour parameters and plantation characteristics were roughly explained by the different model parameters, that tree age was the main plantation characteristic that determines the redness and lightness indexes of wood colour of *T. grandis*, but cluster sites affected mainly the yellowness index (b^*) of heartwood. DBH affected the coordinates of wood colour in heartwood, having the greatest effect in lightness index (10.1%). Growth rate affected only a^* coordinates in heartwood (Tab. VI).

Sapwood was less affected than heartwood by plantation characteristics. Only a^* (redness) was affected, for several plantation characteristics (Tab. III), but some tree variables were highly significant (Tab. IV). As was mentioned above, the difference in colour between heartwood and sapwood is due to the process of heartwood formation, with the extractives produced accumulating in the heartwood, resulting in colour (Gierlinger et al., 2004). The process depends on several factors, such tree age, soil composition and location with in a tree. Some precursors of the synthesis of extractives are located in sapwood tissue, but the content is lower than in heartwood (Gierlinger et al., 2004).

For various other species, tree age, DBH, and growth rate have shown significant correlations with colour parameters, similar to the *T. grandis* results. For example, Gierlinger et al. (2004), studying hybrids of Japanese larch, have shown that old trees have significant redder hue (a^*) than young trees. Also, they determined that slowly grown mature trees from native sites had higher a^* and b^* values, compared with young rapidly grown plantation trees. Klumpers et al. (1993) found that the heartwood became increasingly redder (a^*) with age in *Quercus robur*. On the other hand, growth rate was negatively correlated with a^* but not with L^* or b^* in *Calycophyllum spruceanum* growing the Peruvian Amazon (Sotela et al., 2008). Wilkins and Stamp (1990) reported that faster growing trees of *Eucalyptus grandis* produced redder heartwood (increasing a^*). Rink (1987) found that faster growing trees of *Juglans nigra* produced lighter coloured heartwood.

The low correlation coefficients found between wood colour coordinates and plantation characteristics in heartwood suggests that for wood colour in *T. grandis,* other factors may have a larger influence, such as genetics, environment or soil conditions. For example, Nelson et al. (1969) found wood colour in *Juglans nigra* is associated with soil properties but is independent of growth rate and tree age. Recently, Phelps et al. (1983) and Gierlinger et al. (2004) observed that in *Juglans nigra* and several species of *Larix*, great differences were found in colour coordinates between the sites. These results agreed only with b^* in *T. grandis*. Additionally, wood colour can be influenced by genetic factors that were not considered in these studies. There are few studies on genetic effects on wood colour in tropical species. For *Calycophyllum spruceanum*, Sotela et al. (2008) reported that wood colour had relatively low heritability for L^* and that no significant correlations were determined for a^* and b^*.

3.5. Relation between colour and decay resistance

The values of weight loss from exposure to *Trametes versicolor* and *Pycnoporus sanguineus* are plotted for L^* and a^* in Figure 4; b^* was not plotted because no correlation was determined with weight loss (Tab. VI). Note the positive relationship between weight loss and L^* and the negative relationship between weight loss and a^* for both white rot fungi (Figs. 4a and b). As L^* and a^* were negatively correlated (Fig. 2a), there is a negative correlation between weight loss and a^* coordinates (Figs. 4c and d), confirmed by the Pearson coefficients for sapwood and heartwood (Tab. VI). The greatest correlation coefficients were found when all samples were considered together ($r > 0.62$), and lower coefficients were found for sapwood and heartwood considered separately (Tab. VI).

Several studies on the correlation between colour and durability have been investigated for heartwood (Bhat et al., 2005;

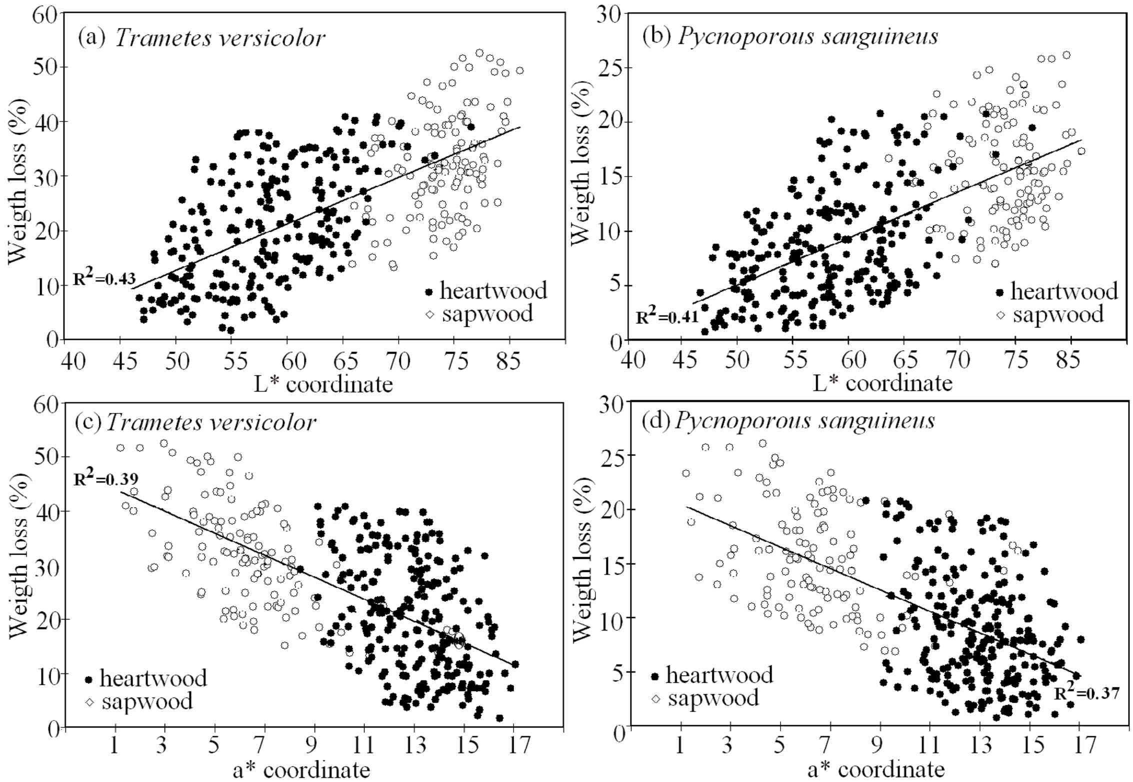

Figure 4. Relationship between L^* and a^* coordinates of *Tectona grandis* and its weight loss for *Trametes versicolor* and *Pycnoporus sanguineus* white-rot (N sapwood = 127 and N heartwood = 267).

Kokutse et al., 2006; Lukmandaru and Takahashi, 2008), although they did not include the effect of sapwood colour on decay resistance. Our finding of an increase in L^* in heartwood (Fig. 4a), was also demonstrated by Bhat et al. (2005) and Kokutse et al. (2006) for several brown- and white-rot fungi and with termites (Lukmandaru and Takahashi, 2008). However, conflicting results have been found for a^* and b^* coordinates. The b^* coordinate was not correlated with *P. sanguineus* attack resistance (Tab. VI), whereas Kokutse et al. (2006) found significant effects for the same fungus. However, the significance of a^* and b^* colour parameters could depend on the species of fungi, and for this reason we agree with Kokutse et al. (2006) that "the colour parameters for redness and yellowness were not good indicators of durability in teak wood".

Gierlinger et al. (2004) proposed that the relationship between colour and decay resistance is indirect, based on the influence of extractives on both. This can be applied to heartwood, but not sapwood. Many studies have demonstrated that extractives such as tectoniquinone, naphthoquinone, and extractives soluble in petroleum-ether, methanol, acetone/water, and ethanol/water affect decay resistance in heartwood, and they vary from pith to bark (Haupt et al., 2003; Lukmandaru and Takahashi, 2008; Thulasidas and Bhat, 2007). Sapwood decay resistance is more complex, and we found that L^* and a^* were correlated with *T. versicolor* attack and a^* was correlated only with *P. sanguineus* (Tab. VI, Fig. 4). However, no correlations were determined between coordinates of wood colour and distance from the pith (Fig. 4). Histochemical studies on sapwood and heartwood and their transition zone have been carried out for *T. grandis*. It was shown that different peroxidase, adenosine triphosphatase, extractives, and chemical components varied within sapwood and sapwood/heartwood transition (Datta and Kumar, 1987). The sapwood is attacked by fungi because of starch and soluble carbohydrates such as glucose and fructose (Rudman and Da Costa, 1959). The amounts of these compounds vary from outer sapwood to inner sapwood. Also, the presence of some extractives, like tectonoquinone, one of the extractives most likely responsible for durability, is synthesized in the sapwood and its concentration varies in sapwood (Lukmandaru and Takahashi, 2008).

On the other hand, Rudman and Da Costa (1959) established, based on extracted samples, which decay resistance is due to a gradual change either in cell composition or structure as the tree ages (Moya et al., 2009).

4. CONCLUSION

Wood colour variation from pith to bark is a linear combination of L^* and a^* coordinates in sapwood and heartwood of *T. grandis*. The variation of L^* and a^* indicated different decay resistance. Darker (high values for L^*) and redder (high positive values for a^*) is the wood, higher is the decay resistance.

Plantation characteristics affect mainly a^* and L^*. Although age and height of trees, growth rate, DBH, and plantation density significantly affect these coordinates, tree age is the main factor in plantations. b^* measured in the heartwood was influenced by different plantation sites. Therefore, the wood colour variation in *T. grandis* is controlled by age of the tree, and through some methods of plantation management, we can control the L^* and a^* coordinates, which produce changes in wood colour. Also, plantation site can control L^*, with less influence in wood colour variation. With colour controled by site selection, plantation density or growth rate, we can provide timber with a better decay resistance.

Acknowledgements: The authors wish to thank The Research Vice-Rectory of the Technological Institute of Costa Rica (ITCR), and Precious Woods of Central America (MACORI), Ecodirecta Groups and Panamericans Woods for financial support in soil analyses. And Frank Beall (SWST) and Mike Wiemann (Forest Products Laboratory USDA) for his comments and recommendations in this article.

REFERENCES

ASTM-Amersican Society for Testing and Materials, 2003. Standard method of accelerated laboratory test of natural decay resistance of woods (ASTM D 2017-81 Reapproved 1994). Annual Book of ASTM Standards, Vol. 04.10, Philadelphia, USA, pp. 445–457.

Bhat K.M., 1999. Is fast grown teak inferior in wood quality – An appraisal of wood figure (colour, grain, texture) from plantations of high input management. Wood News 9(4): 48–49.

Bhat K.M., 2000. Timber quality of teak from managed tropical plantations with special reference to Indian plantations. Bois et For. des trop. 263: 5–15.

Khat K.M., Thulasidas P.K., and Florence E.J., 2005. Wood durability of home-garden teak against brown-rot and white-rot fungi. Trees 9: 654–660.

BYK-Gardner L., 2004. CIE $L^*a^*b^*$ system. Color-guide 45/0 operating instructions, MD, USA, pp. 1–67.

Datta S.K. and Kumar A., 1987. Histochemical studies of the transition from sapwood and heartwood in *Tectona grandis*. IAWA Bull. n.s. 8(4): 363–368.

FAO, 2006. Global planted forest thematic study: results and analysis, In: Del Lungo J.B. and Carle J. (Eds.), Planted Forests and trees: Working paper 38, Rome.

Gierlinger N., Jacques D., Gradner M., Wimmer R., Schwanninger M., Rozenberg P., and Pâques L.E., 2004. Colour of larch heartwood and relationships to extractives and brown-rot decay resistance. Trees 18: 102–108.

Gonnet J.F., 1993. CIELab measurement, a precise communication in power colour: an example with carnation (*Dianthus caryophyllus*) cultivars. J. Hort. Sci. 68: 499–510.

Haupt M., Leithoff H., Meiser D., Richter H.G., and Faix O., 2003. Heartwood extractives and natural durability of plantation-grown teakwood (*Tectona grandis* L.) – a case study. Holz Roh. Werkst. 61: 473–474.

HunterLab, 1995. Use measurement of apparence, A Wiley-Interscience publication, Wiley and Sons, New York, 345 p.

Johansson D. and Morén T., 2006. The potential of colour measurement for strength prediction on thermally treated wood. Holz Roh Werst. 64: 104–110.

Klumpers J., Janin G., Berker M., and Lévy G., 1993. The Influences of age, extractive content and soil water on wood color in oak: the possible genetic determination of wood color. Ann. Sci. For. 50 (Suppl.1): 403s–409s

Kokutse A.D., Stokes A., Baillères H., Kokou K., and Baudasse C., 2006. Decay resistance of Togolese teak (*Tectona grandis*) heartwood and relationship with colour. Trees 20: 219–223.

Liu S., Loup C., Gril J., Dumonceaud O., Thibaut A., and Thibaut B., 2005. Studies on European beech (*Fagus sylvatica* L.). Part 1: Variations of wood color parameters. Ann. For. Sci. 62: 625–632.

Lukmandaru, G. and Takahashi K., 2008. Variation in the natural termite resistance of teak (*Tectona grandis* Linn. fil.) wood as a function of tree age. Ann. For. Sci. 65: 1286–1296.

Möttönen V., Alvila L., and Pakkanen T.T., 2002. CIE $L^*a^*b^*$ measurements to determine the role of felling season, log storage and kiln drying on coloration of silver birch wood. Sand. J. For. Res. 17: 179–191.

Mazet J.F. and Janin G., 1990. La qualité de l׳aspect des placages de Chênes (*Quercus petraea* and *Quercus robur*): mesures de couleur et critères de d׳appréciation des professionnels français et italiens. Ann. Sci. For. 47: 255–268.

Moya R., Berrocal A., Serrano R., and Tomazello M., 2009. Radial variation of anatomical features, wood density and decay resistance in teak (*Tectona grandis*) from two qualities of growing sites and two climatic regions of Costa Rica. Invest. Agrar.: Sist. Recur. For. 18(2): 64–77.

Moya R. and Pérez D., 2008. Effect of physical and chemical soil properties on wood characteristics of *Tectona grandis* plantations in Costa Rica. J. Trop. For. Sci. 20(4): 147–155.

Nelson N.D., Maeglin R.R., and Wahlgren H.E., 1969. Relationship of Black Walnut Wood Color to Soil Properties and Site. Wood Fiber 1: 29–37.

Nishino Y., Janin G., Chanson B., Détienne P., Gril J., and Thibaut B., 1998. Colorimetry of wood specimens from French Guiana. J. Wood Sci. 44: 3–8.

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

Pérez D. and Kanninen M., 2005. Stand growth scenarios for *Tectona grandis* plantations in Costa Rica. For. Ecol. Manage. 210: 425–441.

Phelps J.E., McGinnes E.A., Garrett H.E., and Cox G.S., 1983. Growth-quality evaluation of black walnut wood. Part II – color analyses of veneer produced on different sites. Wood Fiber Sci. 15: 177–185.

Rink G., 1987. Heartwood color and quality variation in a young black walnut progeny test. Wood Fiber Sci. 19: 93–100.

Rudman P. and Da Costa W.B., 1959. Variation in extractive content and decay resistance in the heartwood of *Tectona grandis* L.f. J. Inst. Wood Sci. 3: 33–42

Sotela C., Hernández R.E., Beaulieu J., and Weber J., 2008. Genetic variation in wood color and its correlations with tree growth and wood density of *Calycophyllum spruceanum* at an early age in the Peruvian Amazon. New For. 35: 57–73.

Thulasidas P.K. and Bhat K.M., 2007. Chemical extractive compounds determining the brown-rot decay resistance of teak wood. Holz Roh. Werkst. 65: 121–124.

Thulasidas P.K., Bhat K.M., and Okuma T., 2006. Heartwood colour variation in home garden teak (*Tectona grandis*) from wet and dry localities of Kerala, India. J. Trop. For. Sci. 18: 51–54.

Voss D.H. and Hale W.N., 1998. A comparison of the three editions of the Royal Horticultural Society Colour Chart. HortScience 33: 13–17.

Wilkins P. and Stamp C.M., 1990. Relationship between wood colour, silvicultural treatment and rate of growth in *Eucalyptus grandis* Hill (Maiden). Wood Sci. Technol. 24(4): 297–304.