KILN DRYING OF *ACACIA MANGIUM* WOOD: COLOUR, SHRINKAGE, WARP, SPLIT AND CHECK IN DRIED LUMBER

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TENORIO C, MOYA R & QUESADA-PINEDA HJ. 2012. Kiln drying of *Acacia mangium* wood: colour, shrinkage, warp, split and check in dried lumber. *Acacia mangium* is one of the most planted species in tropical countries. However, dried lumber has been limited by high presence of warping, splitting or checking and lack of uniformity in the final moisture content and wood colour. The aim of this research was to investigate the cause of this situation after drying. Climatic conditions where trees grew, height of the tree, grain pattern, drying schedules, distance from pith and heartwood presence were recorded. Initial and final moisture contents, heartwood percentage and shrinkage percentage of board, warp, split and check were also measured. Results showed that colour change of dried lumber was affected by drying schedules and climatic conditions. Width shrinkage percentage of wood was affected by final moisture content, climate, radial wood percentage and relative distance from the pith. Shrinkage percentage of board thickness was correlated with specific gravity, relative distance from the pith and drying schedule. The incidence of boards with twist, bow, split and check increased after drying. Crook and twist have the highest incidence rate. The quality parameters of these boards were affected by climate, grain pattern, initial and final moisture contents and drying schedule. The control of variables with effects on final moisture content, warp and wood colour improved the quality of lumber after drying process.

Keywords: Drying schedule, tropical wood, deformation, distortion, plantation wood, plantation, Costa Rica

TENORIO C, MOYA R & QUESADA-PINEDA HJ. 2012. Pengeringan tanur kayu *Acacia mangium*: warna, pengecutan, sifat meleding, pecah dan retak dalam kayu gergaji kering. *Acacia mangium* merupakan spesies yang paling kerap ditanam di negara tropika. Bagaimanapun, kayu gergajinya sering meleding, pecah atau retak di samping mempunyai kandungan lembapan akhir serta warna yang tidak seragam. Tujuan penyelidikan ini adalah untuk mengenal pasti punca keadaan ini selepas pengeringan. Iklim tempat pokok tumbuh, ketinggian pokok, corak ira, jadual pengeringan, jarak dari empulur serta kehadiran teras kayu kayu direkod. Kandungan lembapan awal dan akhir, peratusan teras kayu, peratusan pengecutan, meleding, pecah serta retak turut diukur. Keputusan menunjukkan bahawa perubahan warna kayu gergaji kering dipengaruhi oleh jadual pengeringan serta keadaan iklim. Pengecutan lebar papan dipengaruhi oleh kandungan lembapan akhir, iklim, peratusan kayu jejari serta jarak relatif dari empulur. Pengecutan ketebalan papan berkait dengan graviti tentu, jarak relatif dari empulur dan jadual pengeringan. Kejadian memulas, melengkung sabut, pecah dan retak meningkat selepas pengeringan. Kayu paling banyak bengkok dan memulas. Parameter kualiti papan dipengaruhi oleh iklim, corak ira, kandungan lembapan awal dan akhir serta jadual pengeringan. Kawalan pemboleh ubah yang memberi kesan terhadap kandungan lembapan akhir, sifat meleding serta warna kayu dapat meningkatkan kualiti kayu gergaji selepas proses pengeringan.

INTRODUCTION

Wood drying is an important stage of the manufacturing process as it contributes towards lumber dimensional stability, workability, finish and adhesive wettability. This process also improves thermal, acoustic and electric insulation properties as well as mechanical properties and resistance to decay (Gu et al. 2004). Throughout the drying process, it is necessary to adequately control all stages that make up this process in order to reduce variations in the wood colour as well as preventing drying defects (Simpson 1999, Gu et al. 2004). Low quality of dried lumber not only affects monetary value of the wood but also several of its workability properties including planing, shaping, turning, boring, mortising and sanding (Gu et al. 2004). Wood

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colour must also remain as uniform as possible to ensure esthetic effect (Keey 2005). Factors that cause changes in wood colour and drying defects include wood species characteristics such as density and chemical composition (Möttönen 2006), presence of extractives (Burtin et al. 1998, Luostarinen & Möttönen 2004, Keey 2005), tree age (Qumruzzaman et al. 2005), longitudinal position of the log in the standing tree (Ofori & Brentuo 2005), initial moisture content of wood (Ofori & Brentuo 2005, Moya & Muñoz 2008), drying schedule (Simpson 1999, Gu et al. 2004), and presence of sapwood and heartwood (Yamamoto et al. 2003) as well as wetwood (Gu et al. 2004).

Acacia mangium has had good acceptance in Asia, Africa, Central and South America as well in the Caribbean (Arisman & Hardiyanto 2006). Its success in commercial plantations lies in its rapid growth and ability to grow in marginal and burnt soils as well as abandoned agricultural fields (Newaz et al. 2005). The logs can be easily sawn, drilled, turned and polished (Qumruzzaman et al. 2005) and the heartwood is moderately resistant to preservative treatment (Keating & Bolza 1982). The sapwood and heartwood have distinct coloration. The sapwood is often white or yellowish-white and the heartwood is yellowish brown to golden brown when fresh, to dull brown upon long exposure. This species is hard, dense and relatively straight-grained and the green wood density ranges from 400 to 480 kg m^{-3} while its air-dry density, from 500 to 600 kg m^{-3} (Sahri et al. 1993). *Acacia mangium* is used as raw material for pulp and paper but due to its good mechanical properties it can be used as a structural material (Arisman & Hardiyanto 2006). However, there are several problems with *Acacia* wood from plantation trees and these include lumber quality and problems in some industrial processes including wood drying (Moya et al. 2008, Basri & Yuniarti 2009). The number of wood defects such as check (end-grain surface and extending along the length of a board), cup (warp across the width of the face of a piece of lumber) and crook (warp along the length of the edge of lumber) in *A. mangium* board increases after drying, and it is higher than other species from rapid growth plantations in tropical regions (Moya et al. 2008). Pre-drying before conventional drying could reduce drying-related problems (Lim et al. 2003). On the other hand, it was also reported that *Acacia* lumber had high incidence of collapse and splits (separation of fibre caused by the tearing apart of wood parallel to the wood rays) and pre-drying was recommended for this species before kiln drying, in addition to a slow-drying schedule (Piao et al. 2000).

Acacia mangium lumber obtained from thinning and clear cuts of fast-growing plantations developed severe drying defects (Basri & Wahyudi 2007). Possible factors contributing to changes in wood colour induced by drying have not been studied. Thus, the purpose of this study was to determine variation in shrinkage, warp, split, check and wood colour of *A. mangium* after kiln drying. Factors such as climatic conditions, drying schedule, position of the log in the tree, distance of the board from the pith, grain pattern, initial and final moisture contents, diffusion coefficient, and presence of sapwood and heartwood were also investigated. The information obtained will reveal the causes of shrinkage in boards as well as the presence of warp, split and check in the lumber after drying. This information should be taken into consideration in order to understand wood colour variation and to reduce defects and ensure uniform drying of this tropical species.

MATERIALS AND METHODS

Plantation location, characteristics and tree sampling

Two rapid growth *A. mangium* plantations located in different climatic conditions in Costa Rica and belonging to Ganadera Basa SA were selected for study to represent wet and moist zones (according to Holdridge 1967). The former is situated in the country's northern region while the other, the central Pacific region. Both plantations were nine years old and had similar management conditions. However, morphological characteristics of their trees differed (Table 1). The plantation characteristics were obtained from two temporary plots established in the plantation. Ten trees per site were felled and two 2.5-m long logs were cut from each tree: the first from the base of the tree to the height of 2.5 m (height A) and the second starting at 2.5 m and ending at 5.0 m (height B).

Log sawing pattern and sampling

Logs were sawn using a pattern to produce 25-mm thick boards with the different orthotropic directions commonly used in Costa Rica for the furniture industry (Figure 1a). Distance from the pith was measured to establish board location in relation to log radius (relative distance). A total of 216 boards were obtained from both sites. Each board was cut at a distance of 30.5 cm from the lower end of the board (Figure 1c) and then two transversal sections were obtained from small boards (30.5 cm in length); one was 2.5 cm thick, used to determine initial moisture content and the other, 3 mm thick to determine type of grain pattern and the presence of heartwood and/or sapwood (Figure 1c). In addition, three 2 × 2 × 2 cm pieces were cut from the 27-cm section for the determination of specific gravity (SG), radial and tangential diffusion coefficients (RDC and TDC respectively) and radial and tangential shrinkage (RS and TS respectively).

Board classification and determination of heartwood and sapwood percentages

Using grain patterns of the transversal section of the 3-mm section, boards were classified as flat sawn, radially sawn, rift sawn or double rift sawn (Figure 1b). A 512-dpi digital photograph of each sample was taken together with a calibrated ruler (± 0.5 mm). The Image Tool Software® was used to calculate the total section area as well as heartwood and sapwood areas and percentages. The photograph was also used to determine the

Table 1 Characteristics of the fast-growing *Acacia mangium* plantation used in the study

Characteristic	Parameter	Climate	
		Wet zone	Moist zone
Environmental condition*	Average temperature (°C)	18–24	24–30
	Average rainfall (mm $year^{-1}$)	4000–8000	2000–4000
	Dry season	March–April	January–April
Plantation characteristic	Tree age (years)	9	9
	Plantation density (trees ha^{-1})	265.26	287.37
	Diameter at breast height (cm)	30.55 (4.33)	25.26 (3.19)
	Sample tree height (m)	24.01 (0.01)	21.65 (3.09)

*Climatic data taken from the Holdridge (1967); values in parentheses are standard deviations

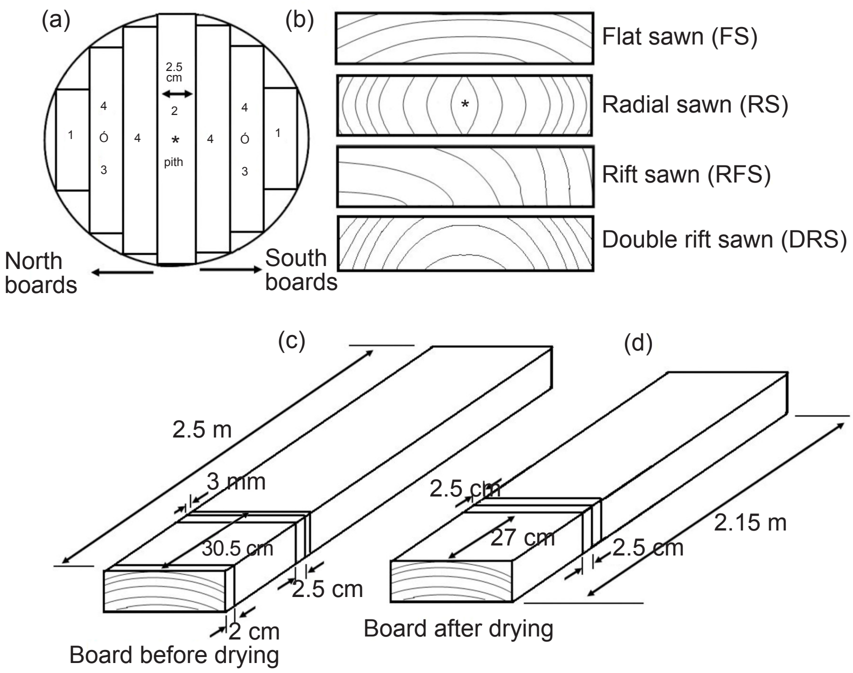

Figure 1 Sawing pattern used in each log and sample obtained for determination of moisture content

tangential and radial areas of the transversal section of the board and these data were used to calculate the grain pattern percentages.

Wood drying and determination of moisture content

Two drying schedules were used. The first schedule (DS1) was applied to boards from the south-facing side of the log and is a combination of the T3-D2 and T8-D2 drying schedules proposed by Boone et al. (1988). The second schedule (DS2) was applied to boards from the north-facing side of the log and was designed based on results of the first schedule (Table 2). Moisture content was calculated before and after drying. In order to determine the initial moisture content, the 2.5-cm transversal section obtained from the lower end of each board was used. Final moisture content was calculated using a 2.5-cm transversal section obtained from the upper end of the dried lumber (Figure 1d). Moisture content was determined using standard ASTM D-4462-92 (ASTM 2003b).

Determination of wet pockets

Wet pockets, also known as water pockets, are found in dried wood of some species. Wet pockets are zones with 10% or higher than average moisture content (Simpson 1991). Once the drying process was completed, another transversal cut approximately 2.5-cm thick was made at a distance of 27 cm from the lower end of the board (Figure 1d) in order to assess the presence of wet pockets. Due to the high moisture content, wet pockets caused a difference in surface colour of the dry wood. Borders of wet pockets were contoured on this transversal section and a digital photograph was taken. Image Tool Software® was used to calculate the wet pocket area and total area of cross-section of this transversal area. Wet pocket area was expressed in relation to total area.

Determination of wood colour

Colour was measured in each of the 216 boards using a spectrophotometer which was calibrated after each use. Board was sanded with 120-grit aluminum-oxide paper-back belt in the middle across the width and middle of length. Board colour was measured before (~127% moisture content) and after (~12%) drying in this position. All wood colour measurements were taken using the heartwood boards because the trees used in this study had a high percentage of heartwood (88%) and

Table 2 Kiln schedules used for the conventional drying of *A. mangium* wood

Step	Drying schedule 1			Drying schedule 2		
	TBS (°C)	EMC (%)	MC (%)	TBS (°C)	EMC (%)	MC (%)
Heating	40		-	45		-
	42	18.5	-	50	19.5	-
Drying	44	18.5	55	55	18.5	55
	44	17.6	50	55	17.6	50
	44	17.0	45	55	17.0	45
	44	16.3	40	55	16.3	40
	44	13.6	35	55	13.6	35
	44	9.9	30	55	10.1	30
	49	5.5	25	60	5.8	25
	55	4.0	20	66	4.0	20
	60	2.9	15	71	3.4	15
	71	3.5	12	82	3.5	12
Equalisation	71	10	10	82	10	10
Conditioning	71	13	-	82	12	-
Cooling	40	-	-	40	-	-

TBS = Dry-bulb temperature, EMC = equilibrium moisture content, MC = moisture content a very small percentage of sapwood (12%). Despite the presence of sapwood in the logs, the sawing pattern applied to obtain the boards (Figure 1a) largely reduced the sapwood content of most boards, so a large number of boards contained only heartwood.

The CIEL*a*b* system was used to measure the reflectance spectra. Using the three dimensional CIEL*a*b* colour space, each colour can be expressed as a point in three coordinates correlating with subjective colour perception. Coordinate L* for lightness represents the position on the black–white axis (L = 0 for black, L = 100 for white), while the chroma value a* defines the position on the red–green axis (positive values for red shades, negative values for green shades), and b* on the yellow–blue axis (positive values for yellow shades, negative values for blue shades). Loss of lightness is observed as a smaller value of L*. The larger the value of a*, the more red chroma is observed. Large b* values represent a strong presence of yellow chroma. On negative sections of the chroma scales a* and b*, an intense green colour is expressed with a great negative value of a*, and for a bright blue, b* becomes large with a negative sign. Zero values for a* or b* denote absence of redness/greenness or yellowness/blueness (Mononen et al. 2002). Spectral range was between 400 and 700 nm, with an 11-mm opening at measurement point. In order to observe reflectance, the specular component (SCI mode) was included at a 10° angle (D65/10), a 2° field of vision (CIE 1931 Standard Observer) and D65 standard illumination (corresponding to daylight 6500 K).

The change in colour after drying (ΔE*) was expressed as the distance between two points in the colour coordinate and was calculated from the split up values ΔL*, Δa* and Δb*. The value of ΔE* was classified into five different levels according to the human eye, following the measurement suggested by Cui et al. (2004):

ΔE*	Level of change
0–1.5	Imperceptible
1.5–3.0	Barely perceptible
3.0–6.0	Perceptible
6.0–12.0	Very evident
> 12	Different

Determination of specific gravity and diffusion coefficients

Samples measuring 2 × 2 × 2 cm were used to determine SG (oven dry mass/green volume), RDC and TDC. The SG was determined in accordance with standard ASTM-143 (ASTM 2003a). To calculate RDC and TDC, the four faces of the sample were sealed with paraffin and the remaining opposing tangential or radial faces were left unsealed. The unsealed faces allowed water to diffuse in a tangential or radial direction, as desired. Samples were weighed at the beginning and then at three-hour intervals during the first 48 hours and thereafter at every 24 hours until their weight remained constant. Finally, these samples were dried at 105 °C over a period of 24 hours in order to determine their dry weight. Diffusion coefficient (D) was calculated for each direction using equation 1 (Stamm & Raleigh 1967):

$$D = \frac{E_t^2 \times \pi}{16 \times t \times L^2} \quad (1)$$

where

L = sample length in the direction of water diffusion (mm)
t = drying time (s)
E = relative change in wood moisture content from green to dry (15%)

Shrinkage

Two different shrinkage measurements were conducted. One was measured on radial and tangential oriented samples and the other, on each dried boards. Tangential and radial shrinkage was measured in samples used to determine RDC and TDC. These samples were measured in green conditions in tangential or radial orientation and they were oven dried at 103 °C for 24 hours (ASTM 2003a). The shrinkage of each board was determined in relation to the board thickness and width. These dimensions were measured in the middle of the board and they were measured from green to dried condition. Board shrinkage was determined by the dimensional change in board width and thickness from green to dried condition.

Determination of warp, split and check

Twist (a distortion in which the two extremes do not lie on the same plane), crook, cup and bow (warp along the length of the face of lumber) as well as splits (separation of fibre caused by the tearing apart of the wood parallel to the wood rays) and checks (end-grain surface and extending along the length of a board) were measured (Hallock & Malcom 1972, Milota 1996) in each board (n = 216) before and after drying and considered as quality parameters. For warp measurement, each piece was positioned on a flat table to examine the extent of each warp type. If the amount of warp appeared so small that a meaningful determination seemed implausible, a judgment of 'no warp' was assigned. When a measurement was judged to be required, it was made via the insertion of a calibrated inclined plane wedge. With the wedge inserted to the point of mild refusal, the measurement was read of the calibrated vertical face of the wedge (Shmulky & Dahlen 2007).

Twist, crook, cup and bow values were first reported according to magnitude of the defect and then number of defective boards in relation to total number of pieces. Defect magnitude after drying was classified either as decreased, increased or remained the same in relation to those values exhibited by the boards before drying. The official Chilean standard was used to determine the severity of twist, crook, cup and bow parameters. This standard sets limit quality values for the different parameters. These values were described by Pérez et al. (2007). Once the parameters were quantified in relation to the different value categories, a quality index for each parameter (equation 2) was established in accordance with Chilean Standard Nch993EO72 (Pérez et al. 2007).

$$I = (Na \times 0) + (Nb \times 0.5) + (Nc \times 2) + (Nd \times 2.5 M) \quad (2)$$

where

I = quality index
Na = number of pieces without any presence of warp, split or check
Nb = number of pieces with a slight presence of warp, split or check
Nc = number of pieces with a moderate presence of warp, split or check
Nd = number of pieces with a severe presence of warp, split or check
M = total number of pieces

In the case of splits and checks, the American Softwood Lumber Standard PS 20-05 (NIST 2005) was used, although application was for *A. mangium*, a hardwood species. This standard classifies these quality parameters into three categories according to this value. For checks, the categories were: not present (0 mm), mild (1–10 mm), moderate (10–25 mm) and severe (over 25 mm). For splits, the categories were: not present (0 mm), mild (1–25 mm), moderate (25–42 mm) and severe (over 42 mm).

Statistical analysis

Special attention was focused on the assumption of normal distribution, variance homogeneity and absence of extreme data. This was done using the SAS System PROC UNIVARIATE procedure Version 8.1 for Windows. To analyse effects of the different factors on colour parameters, a correlation analysis was first conducted for random effects or quantitative factor and then a second analysis was carried out for those random factors where the independent variables were corrected by statistically significant random factors (drying schedule, location of log in tree, grain pattern and growth climate). To do so, an analysis of covariance (ANCOVA) was conducted. Distance of boards from pith, heartwood percentage, radial and tangential wood percentages, SG and shrinkage (independent variables) were considered in the correlation analysis for colour parameters before drying (dependent variables). Dependent variables after drying (quality parameters of boards and colour parameters) were once again correlated with the aforementioned independent variables as well as initial and final moisture contents, RDC and TDC. Statistical differences between means were obtained using LSMEANS methods derived from the ANCOVA.

The quality index (equation 2) was used for analysing drying quality parameters. Location of log in tree, grain pattern and tree growth climate were considered in ANOVA. However, in addition to these three factors and in the case of dried lumber, the drying schedule was added as a variable. The influence of these factors was evaluated by means of an analysis of variance, where the quality index was the independent variable and the above-mentioned factors were the independent variables.

RESULTS AND DISCUSSION

Initial and final moisture contents

Average initial moisture content was 127% and ranged between 58 and 186% (results not shown). This range is greater than that reported by Moya et al. (2008), who found a variation between 110 and 184% for nine-year-old *A. mangium* growing in Costa Rica. In reaching the final moisture content, the duration for DS1 and DS2 was 379 and 337 hours respectively. The average final moisture content for both drying schedules was 19% but the range was large, i.e. between 9 and 52% (results not shown). These results showed a lack of uniformity in the final moisture content of *A. mangium* dried lumber with both drying schedules. High moisture content was also reported by Moya et al. (2011) for dried lumber in wood of nine-year-old *A. mangium.* Although variations in final moisture contents occur in dried lumber they must be minimised in order to improve lumber stability and final product quality. This limited uniformity in final moisture contents can have significant impact on secondary wood processing and final product performance (Arisman & Hardiyanto 2006). Drying is deemed satisfactory when the average final moisture content is ± 1% (Muñoz & Moya 2008). Therefore, *A. mangium* in this study did not reach a satisfactory level.

Acacia mangium is known for its high initial moisture content, presence of wetwood and high variation in the moisture content (Yamamoto et al. 2003, Tenorio & Moya 2011). This leads to longer and irregular drying process resulting in a final moisture content that is higher than scheduled, usually greater than 19% (Ward 1986).

The formation of wet pockets in dried lumber is an important factor affecting final moisture content and shows that this species is prone to developing wet pockets during drying. In dried *A. mangium* lumber, this study found that 64% of the evaluated 216 boards had wet pockets. Wet pockets in dried *A. mangium* lumber can be observed transversely and throughout the entire length of the board. They are darker in colour than the drier portions of the board (Figure 2). When assessing moisture content in the area inside and surrounding the wet pocket, it was found that average moisture content inside the wet pocket was 25% (12–76%) while outside, the value was 16% (12–22%). The average wet pocket area in the transversal section was 23%. Wet pockets have been reported in dried lumber from other plantation species in Costa Rica such as *Gmelina arborea* (Moya & Muñoz 2008) and *Vochysia guatemalensis* (Moya et al. 2011). These studies reported variations in moisture content inside wet pockets to be as high as *A. mangium* in the current study, i.e. between 40 and 100% and 15 and 35% respectively.

Wood colour

All three heartwood colour parameters (L*, a* and b*) increased significantly after drying compared with their values before drying (Figure 3a). Parameter L* increased from 37.39 (± 6.94 SD, 21.18 min, 61.53 max) to 46.10 (± 5.27, 31.58 min, 69.37 max), b* from 16.21 (± 4.00, 5.93 min, 29.64 max) to 24.67 (± 3.39, 17.36 min, 46.17 max) and finally a* from 6.86 (± 2.42, 1.07 min, 13.50 max) to 8.98 (± 1.82, 4.09 min, 15.04 max). The increment in colour parameters of this study differed from colour change of other tropical species such as *V. guatemalensis* or *Tectona grandis* (Aguilar et al. 2009, Moya & Berrocal 2010 respectively) where lightness (L*) usually decreased and redness

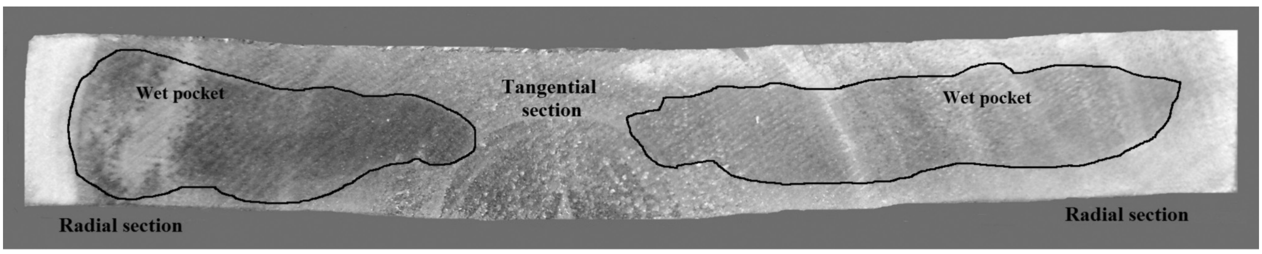

Figure 2 Wet pocket in dried wood of *Acacia mangium* for double rift sawn board

(a*) and yellowness (b*) increased. However, Aguilar et al. (2009) showed that after drying *V. guatemalensis*, the lightness of its heartwood increased from 68.1 to 70.7 and yellowness from 22.1 to 22.3 but redness decreased from 6.9 to 6.7. They reported a similar trend for *A. mangium* for L* and b*, but a* was different from *A. mangium.*

The change in colour after drying experienced by this lumber can be quantified by means of ΔE*. The colour classification by Cui et al. (2004) showed that only 1% of the total number of kiln-dried *A. mangium* boards underwent a change in colour that was barely perceptible, 9% experienced a perceptible change, 31% evident colour change and, finally, 59% of the boards presented a completely changed colour (Figure 3b).

The correlation analysis for the random effects showed that before drying, there was a significant negative correlation between L* and distance from pith and that a* and b* were negatively correlated with the initial moisture content but the latter was positively correlated with board radial percentage (Table 3). After drying, L* showed positive correlation with the percentage of wet pockets, a* correlated positively with SG and negatively with initial moisture content. However, b* was not significantly affected by any factor (Table 3). These random effects did not influence wood colour and were considered controlled factors in the drying process. Wood colour was influenced by two controlled factors, namely, sampling tree height or drying schedule (Table 3).

ANCOVA analysis revealed that before drying, parameter L* was significantly correlated with the height at which the log was obtained and with the interaction between height and grain pattern. Parameter a* was affected by climate and location of log in tree, and b* by location of log in tree. After drying, L* was affected by location of log in tree and drying schedule, a* experienced no change as before drying and b*

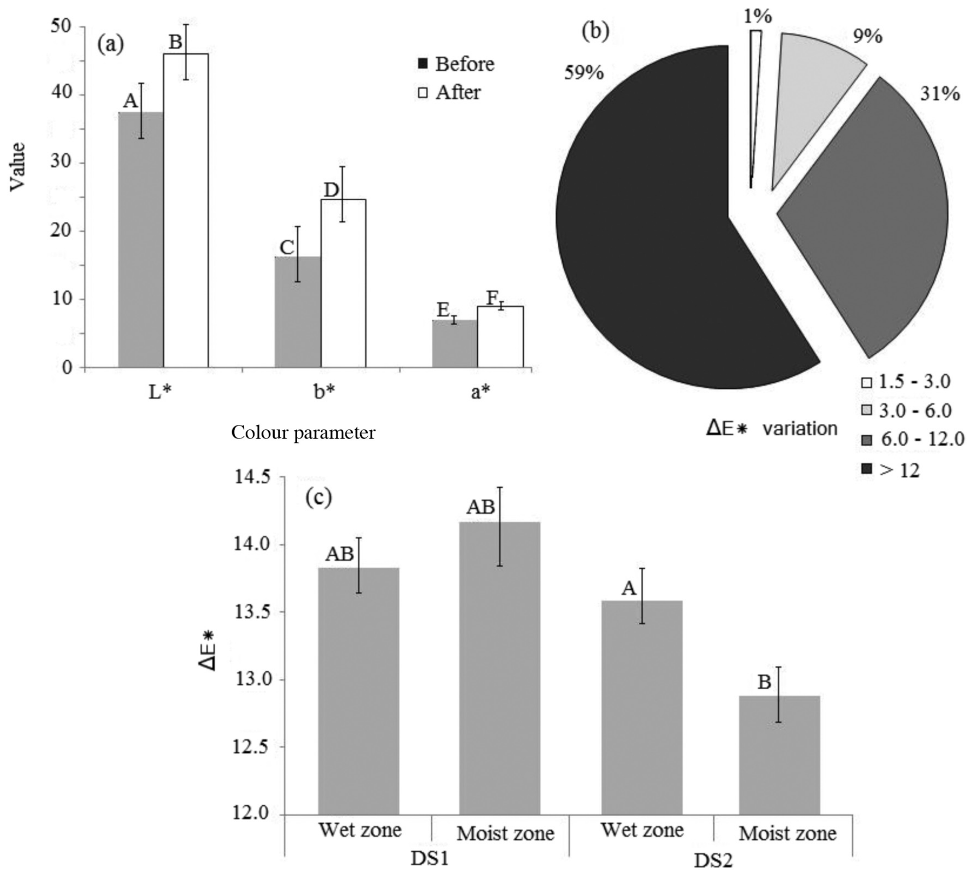

Figure 3 (a) Average colour parameters in *A. mangium* wood before and after drying, (b) ΔE* levels of variation according to the human eye and (c) the ΔE* behaviour for drying schedule (DS) and the type of climate; different letters above the bars in (a) and (c) indicate that values are statistically different at 95% confidence level

Table 3 Pearson correlation coefficients and significance of continuous variables evaluated in the colour and shrinkage of *A. mangium* wood

Factor	Colour before drying			Colour after drying			ΔE*	% Shrinkage	
	L*	a*	b*	L*	a*	b*		Width	Thickness
Initial moisture content	-0.197	-0.419**	-0.221*	0.141	-0.392**	0.019	0.213	nc	nc
Final moisture content	0.082	0.017	-0.067	0.013	-0.145	0.203	0.041	-0.270**	-0.040
Heartwood percentage	nc	nc	nc	nc	nc	nc	nc	0.060	-0.010
Radial wood percentage	0.183	0.055	0.229*	0.05	-0.087	0.059	-0.145	-0.160*	0.050
Specific gravity	0.062	0.106	0.104	-0.142	0.329**	-0.063	-0.192	0.100	-0.240**
Distance from pith	-0.221*	-0.068	-0.18	-0.224	0.159	0.026	0.201	0.230**	0.160*
Wet pocket	0.069	0.082	0.133	0.220*	0.101	0.063	-0.128	nc	nc
Radial diffusion coefficient	nc	nc	nc	0.013	-0.213	-0.060	-0.054	-0.010	0.270**
Tangential diffusion coefficient	nc	nc	nc	0.034	-0.179	-0.084	0.024	0.010	0.180*
Tangential shrinkage	nc	nc	nc	0.056	-0.156	-0.178	0.015	0.020	0.250**
Radial shrinkage	nc	nc	nc	-0.176	0.056	0.089	-0,099	-0.130	-0.040

nc = not considered in the model; ΔE* = change of colour; *statistically significant at p = 0.05, **statistically significant at p = 0.01

was significantly affected by location of log in tree and climate before and after drying (Table 4). The above results showed that position of the log is the factor that most affected colour parameters before and after drying. The analysis showed that for height B (2.5–5.0 m), the three colour parameters increased their values compared with results for height A (0.0–2.5 m). Thus, lumber from height B log was lighter, redder and yellower than A.

Wood colour change as measured by ΔE* showed no statistically significant relationship with any random factor (Table 3). Of the controlled factors, the ANCOVA indicated that colour change was significant only for the interaction between climate and type of schedule applied (Table 4). In DS1, this interaction resulted in a similar magnitude of colour change in both climate types. However, in DS2 lumber from the wet zone had ΔE* that was significantly higher than lumber from the moist zone (Figure 3c).

Wood colour change is affected by different factors, some pertaining to the tree itself such as site of origin, management, genetics and tree age (Phelps et al. 1983), and others relating to the wood drying process (Mononen et al. 2002, Aguilar et al. 2009). In the first group of factors, site of origin is one of the main sources of colour variation before and after drying (Gierlinger et al. 2004, Moya & Berrocal 2010). Results obtained for *A. mangium* in this study concured with this behaviour because the climate conditions was statistically correlated with colour parameters before and after drying (Table 3). Colour parameters are related to the presence of extractives in wood (Burtin et al. 1998). It has been demonstrated that the amount of extractives in *A. mangium* varies with tree height (Taylor et al. 2002) and, therefore, variations in extractive content may influence colour variations at different height locations of the log. Additionally, colour changes due to grain pattern are the result of colour differences between radial and tangential sections resulting from anatomical characteristics such as cell disposition, existence of wide radial and interlocked grains (Nishino et al. 1998).

With regard to these results, it is important to highlight that the factors correlated with individual colour parameters do not influence wood colour change (ΔE*) (Table 3). Wood surface colour variations might be caused by the elimination of water and movement of extractives from inside to outside and their subsequent oxidation on the surface (Keey 2005). Therefore, the difference in the amount of extractive due to various heights and temperatures used in both drying schedules resulted in colour variations of different magnitude. This was proven by the statistically significant relationship between ΔE* and height and drying schedule.

Table 4 F values of covariance analysis for moisture content, colour and the percentage of shrinkage in *A. mangium* wood (n = 216)

Source of variation		Colour before drying			Colour after drying			ΔE*	% Shrinkage	
		L*	a*	b*	L*	a*	b*		Width	Thickness
Controlled variable	Climate	0.06	6.91**	0.34	0.04	19.39**	8.26**	0.44	12.15**	0.28
	Tree height	16.88**	15.38**	4.36*	11.20**	4.74*	11.98**	3.38	4.91	0.68
	Grain pattern	2.4	0.98	0.64	2.62	1.53	0.75	2.2	0.31	1.15
	Drying schedule	nc	nc	nc	14.52**	0.02	1.33	0.01	1.09	8.32**
	Climate × tree height	0.77	0.15	0.57	0.18	1.08	0.54	0.81	3.89	0.30
	Climate × grain pattern	0.27	0.5	0.5	1.65	0.36	0.55	1.51	0.52	1.69
	Climate × schedule	nc	nc	nc	3.22	0.96	0.03	4.60*	1.32	0.80
	Tree height × grain pattern	2.67*	1.86	2.19	1.54	0.91	2.23	1.03	1.81	0.41
	Tree height × schedule	nc	nc	nc	3.04	1.62	0.47	0.61	0.64	0.46
	Grain pattern × schedule	nc	nc	nc	1.88	0.15	0.85	0.85	1.24	1.36
Random variable	Specific gravity	nc	nc	nc	nc	0.09	nc	nc	nc	0.02
	Distance from pith	0.88	nc	nc	nc	nc	nc	nc	6.51*	0.88
	Radial wood percentage	nc	nc	0.96	nc	nc	nc	nc	0.02	nc
	Initial moisture content	nc	0.16	nc	nc	0.04	nc	nc	nc	nc
	Final moisture content	nc	nc	nc	nc	nc	nc	nc	3.85	nc
	Wet pocket	nc	nc	nc	1.39	nc	nc	nc	nc	nc
	Tangential shrinkage	nc	nc	nc	nc	nc	nc	nc	nc	nc
	Tangential diffusion coefficient	nc	nc	nc	nc	nc	nc	nc	10.76**	18.64**
	Radial diffusion coefficient	nc	nc	nc	nc	nc	nc	nc	nc	2.40

nc = not considered in the model; ΔE* = change of colour; *statistically significant at $p = 0.05$, **statistically significant at $p = 0.01$

Board shrinkage

Board shrinkage averaged 2.3% (± 1.88 SD, 0 min, 9.6% max) in thickness and 2.8% (± 1.92, 0 min, 21.5% max) in width. A correlation analysis of random factors revealed that width shrinkage correlated negatively with final moisture content and radial wood percentage, while relative distance from pith had positive correlation with board-width shrinkage (Table 3). The ANCOVA showed that relative distance from pith (random factor) and climate (controlled factor) affected board shrinkage (Table 4). Boards from trees growing in wet zone exhibited higher shrinkage in width (3.0%) than those growing in moist zone (2.5 %) (Figure 4a) due to a higher final moisture content in the former zone. Highest SG values can be found in trees growing in sites with less precipitation than high precipitation, so lumber from wet zones can present higher shrinkage than moist zones.

Shrinkage of board thickness correlated negatively with SG and relative distance from the pith. RDC and TDC of water and percentage of tangential correlated positively with thickness shrinkage but radial shrinkage was negatively correlated (Table 3). ANCOVA revealed that TDC (random factor) together with type of schedule (controlled factor) significantly affected thickness shrinkage (Table 4). DS2 exhibited a higher shrinkage (2.63%) compared with boards in DS1 (1.96%) (Figure 4b). Shrinkage is directly related to the final moisture content reached in each drying schedule (Simpson 1991). Therefore, boards in DS2 had a lower final moisture content and incidence of wet pockets than boards in DS1.

Wood shrinkage is related to the presence of wood cell wall (Zobel & Van Buijtenen 1989) and SG is an indirect parameter used to measure it. In the case of *A. mangium*, SG is also related to distance from the pith, i.e. it increases from pith to the bark (Kim et al. 2008). The increment observed in SG from pith to bark in this study might be due to the increment in cell wall thickness and decreasing frequency of vessels, which increment was from pith to bark too (Kim et al. 2008). Therefore, a relationship between shrinkage, SG and distance from pith is to be expected; specifically, board shrinkage depends on individual radial and tangential shrinkage values. However, it was found in this study that only thickness was affected by tangential shrinkage (Table 3). It is likely that the presence of random factors affects board shrinkage.

Warp, split and check

Twist, crook, cup, bow and check were observed in *A. mangium* lumber before drying. Crook and twist had the highest incidence rate (> 65%) (Figure 4c). Cup did not occur before drying (Figure 4c). After drying, the incidence of boards with twist, bows, split and check increased. However, crook decreased.

In general, when drying defects were classified according to decreasing or increasing magnitude, it was found that checks, twist, crook and cup remained the same in 40–50% of the boards (Figure 4d). The number of boards with bow and splits decreased after/during drying (Figure 4d).

The classification of quality parameters (Table 5) revealed that a high percentage of boards did not have any warp, split or check. In these cases, the quality was classified as mild, with the exception of crooking which was severe in a high percentage of boards (Table 5). After drying, 92% of boards had mild cupping. Despite the fact that the incidence of boards with warp, split or check increased after drying (Figure 4), the magnitude was lower and, therefore, a high percentage of these lumber was classified as not present in the quality parameters (Table 5). This implied that *A. mangium* lumber defects such as twist, crooks, cupping and check were mild. However, crooking and bowing were severe after drying (Table 5). The above results are in agreement with those found for *A. mangium* by Lim et al. (2003), who pointed out that lumber from this species tends to exhibit defects such as collapse, crooking, bowing, knots and shrinkage in radial and tangential direction after drying. Likewise, other tropical species (Moya et al. 2011) are characterised by an increment in lumber defects from green to dried condition. The authors reported values similar to those obtained in this study for *A. mangium*.

The analysis of controlled factors revealed that crooks and split before and after drying as well as cupping after drying were significantly affected by the type of climate from where the wood came from (Table 6). Bow, split and check after drying were significantly affected by drying schedule. Grain pattern also affected cupping after drying and split before and after drying. The incidence of bow, split or check in *A. mangium* lumber was affected by the drying schedule, climate and grain pattern. Therefore, we can produce dried-lumber with high quality indices in checking

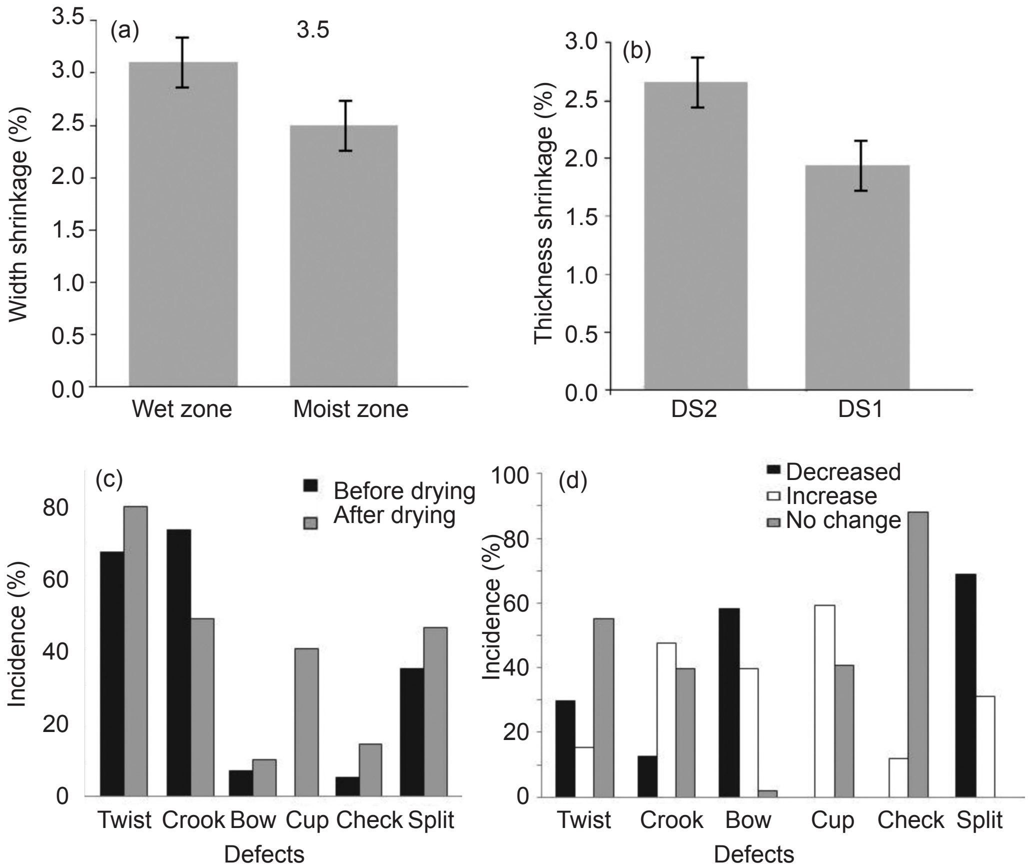

Figure 4 (a) Width shrinkage by climate, (b) thickness shrinkage by drying schedules (DS), (c) incidence percentages of warp, split and check before and after drying, and (d) magnitude of the incidence in the *A. mangium* dried-lumber

Table 5 Percentage of boards in different categories of quality parameters for *A. mangium* boards before and after drying

Quality parameter of board	Condition	Not present	Mild	Moderate	Severe
Twist	Before	67.59	0	27.31	5.09
	After	80.09	14.35	4.63	0.93
Crook	Before	49.07	3.24	9.72	37.96
	After	24.07	0.93	4.17	65.83
Bow	Before	6.94	4.63	18.52	69.91
	After	10.19	5.56	22.22	62.04
Cup	Before	100	0	0	0
	After	0	92.59	4.72	5.56
Check	Before	94.91	3.24	0.93	0.00
	After	85.65	10.35	2.78	1.39
Split	Before	64.81	21.76	6.02	7.41
	After	53.24	31.02	6.02	9.72

Range for twist: not present (0 mm), mild (1–5 mm), moderate (> 5–8 mm) and severe (> 8 mm); crook: not present (0 mm), mild (1–2 mm), moderate (> 2–6 mm) and severe (> 6 mm); bow: not present (0 mm), mild (1–3 mm), moderate (3–6 mm) and severe (> 6 mm); cup: not present (0 mm), mild (1–3 mm), moderate (> 3–5 mm) and severe (> 5 mm); checks: not present (0 mm), mild (1–10 mm), moderate (> 10–25 mm) and severe (> 25 mm); splits: not present (0 mm), mild (1–25 mm), moderate (> 25–42 mm) and severe (> 42 mm) and bowing when using DS2, but quality index increased with DS2 (Figure 5a). On the other hand, quality indices for crook, cup and split defects were higher in the wet climate (Figure 5b). Lumber with tangential grain (rift and double rift sawn) is of good quality in relation to cup parameter. Similarly, double rift and flat sawn grain pattern produced good quality wood in relation to the split parameter (Figure 5c).

The industrialisation of wood from juvenile trees tends to result in high incidence of twist, crook and bow. This is due to their high proportion of juvenile wood. Juvenile wood is characterised by high levels of growth tension (Simpson 1991, Zobel & Sprague 1998). Therefore, it is expected that *A. mangium* lumber will exhibit warping, splitting or checking. Drying of *A. mangium* lumber increased the incidence of certain defects. However, these defects, with the exception of splits, bows and checks, were not affected by the drying schedules used. Nonetheless, caution should be exercised as there were a few differences in the drying rates between these two drying schedules and the presence of warp, split or check was closely related to drying rate (Simpson 1991).

CONCLUSIONS

During the drying of *A. mangium* lumber, heartwood colour changed. Green lumber was darker than dried lumber. This variation was produced by the change in the three colour components (L*, a* and b*). These colour parameters were related to factors such as climate, location of the log in the tree and the drying schedule. However, colour variation (ΔE*) was only related to the drying schedule and climate where the trees grew.

Warp, split, and check and shrinkage in *A. mangium* were classified as either non-existent or mild, with the exception of crooks and bows which were severe. Quality parameters (drying defects) such as twist, crook, cup and board-width shrinkage were not affected by the applied drying schedules. Instead, they were affected by other factors such as climate, grain pattern and initial and final moisture contents. Bow, check, split

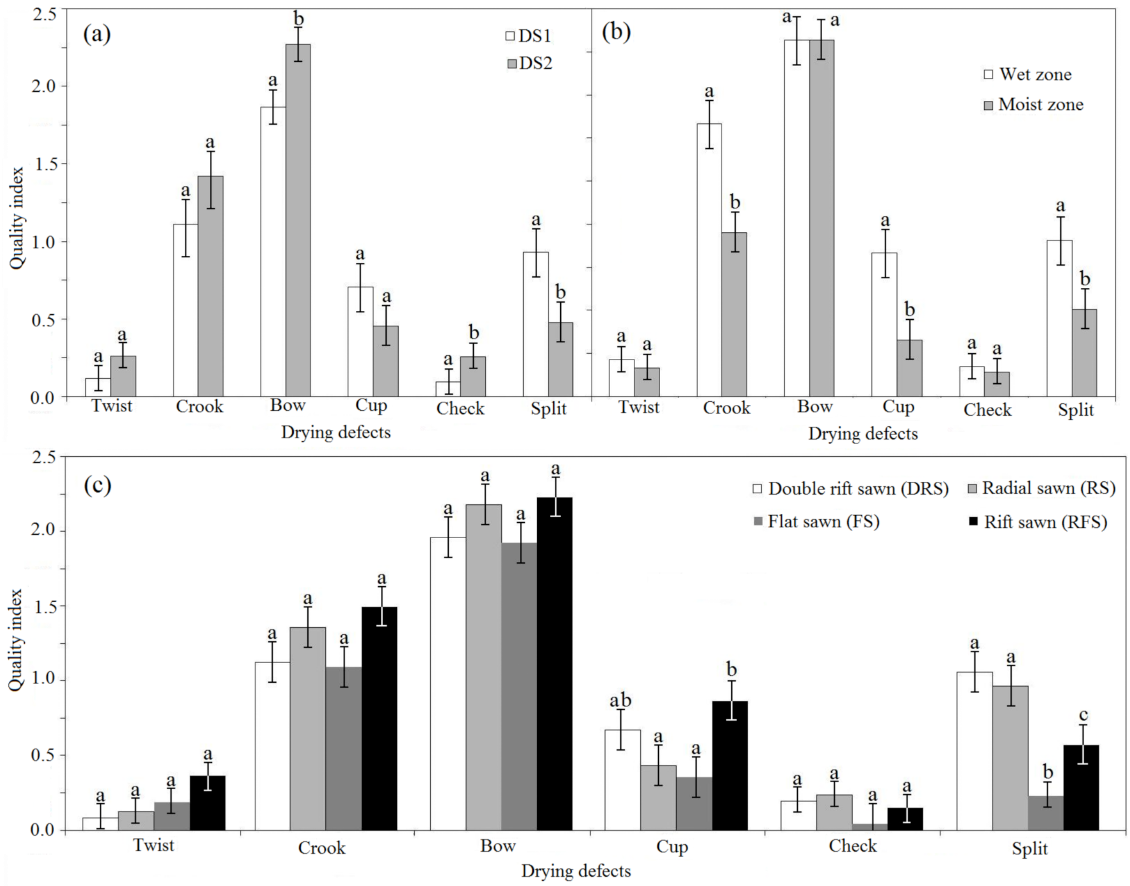

Figure 5 Quality index for all quality parameters of dried lumber of *A. mangium* for (a) two different drying schedules (DS), (b) two climatic conditions and (c) different grain patterns

Table 6 F value of ANOVA for the quality index in *A. mangium* wood before and after drying (n = 216)

Source of variation	Condition	Drying schedule	Climate	Tree height	Grain pattern
Twist	Before	-	0.38	0.00	2.10
	After	3.06	0.41	0.00	2.26
Crook	Before	-	9.98**	1.03	0.92
	After	2.58	10.59**	1.09	0.97
Bow	Before	-	0.00	0.02	1.22
	After	11.88**	0.00	0.02	1.73
Cup	Before	-	0.00	0.00	0.00
	After	3.82	15.14**	0.81	3.25*
Check	Before	-	0.34	0.78	1.25
	After	5.05**	0.11	1.34	0.88
Split	Before	-	7.91**	0.47	4.49*
	After	14.95**	11.62**	0.97	10.60**

**Statistically significant at 99%, *statistically significant at 95%

and thickness shrinkage were affected by drying schedule.

An acceptable dried lumber quality must have uniform final moisture content and heartwood colour as well as lower values of warp, split and checks. Thus, it is necessary to take into consideration the variables that can directly affect (e.g. distance from pith and drying schedule) moisture content, colour, warp, split and check before and after drying. The control of these variables improves the quality of lumber after the drying process. In the case of *A. mangium,* the variables that could be controlled were climate, location of log in the tree (height) and drying schedule.

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REFERENCES

Aguilar D, Moya R & Tenorio C. 2009. Wood colour variation in undried and kiln-dried plantation-grown lumber of *Vochysia guatemalensis. Maderas Ciencia y Tecnología* 11: 207–216.

Arisman H & Hardiyanto EB. 2006. *Acacia mangium*—a historical perspective on its cultivation. Pp 11–15 in Potter K, Rimbawanto A & Beadle C (eds) *Heart Rot and Root Rot in Tropical Acacia Plantations.* Proceedings of a workshop. 7–9 February 2006, Yogyakarta.

ASTM (American Society for Testing and Materials). 2003a. *Standard Test Methods for Test Methods for Small Clear Specimens of Timber. D143–92.* Volume 04–10 (Reproved 2003). ASTM International, West Conshohocken.

ASTM. 2003b. *Standard Test Methods for Direct Moisture Content Measurements of Wood and Wood-Base Materials. D4442–92.* Volume 04–10 (Reproved 2003). ASTM International, West Conshohocken.

Basri E & Wahyudi T. 2007. The drying properties and schedules of five wood species from West Papua. *Jurnal Ilmu dan Teknologi Kayu Tropis* 5: 57–62.

Basri E & Yuniarti K. 2009. The combination of silviculture and drying techniques resulted in good quality of mangium lumbers. *Resumen en XIII Congreso mundial. Buenos Aires Argentina.* Disponible en http://www.cfm2009.org/es/programapost/resumenes/index.asp?offset=2790. (Access 25 August 2010)

Boone RS, Kozlik CJ, Bois PJ & Wengert EM. 1988. *Dry Kiln Schedules for Commercial Woods—Temperate and Tropical.* General Technical Report FPL-GTR-57. USDA Forest Service, Madison.

Burtin P, Jay-Allemand C, Charpentier J & Janin G. 1998. Natural wood coloring process in *Juglans* sp. (*J. regia* and hybrid *J. nigra* 23 × *J. regia*) depends on native phenolic compounds accumulated in the transition zone between sapwood and heartwood. *Trees* 12: 258–264.

Cui W, Kamdem P & Rypstra T. 2004. Diffuse reflectance infrared fourier transform spectroscopy (DRIFT) and colour changes of artificial weathered wood. *Wood and Fiber Science* 36: 291–301.

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

Gu H, Young TM, Moschler WW & Bond BH. 2004. Potential sources of variation that influence the final moisture content of kiln-dried hardwood lumber. *Forest Products Journal* 54: 65–70.

Hallock HY & Malcolm FB. 1972. *Sawing to Reduce Warp in Plantation Red Pine Studs.* Research Paper FLP-164. USDA Forest Service, Madison.

Holdridge L. 1967. *Life Zone Ecology.* Tropical Science Center, San Jose.

Keating WG & Bolza E.1982. *Characteristics Properties and Uses of Timbers. Volume 1. South East Asia, Northern, Australia and the Pacific.* Inkata Press, Melbourne.

Keey R. 2005. Colour development on drying. *Maderas Ciencia y Tecnología* 7: 3–16.

Kim NJ, Ochiishi M & Matsumura J. 2008. Variation in wood properties of six natural acacia hybrid clones in northern Vietnam. *Journal of Wood Science* 54: 436–442.

Lim SC, Gan KS & Choo KT. 2003. *The Characteristics, Properties and Uses of Plantation Timbers Rubberwood and* Acacia mangium. Timber Technology Bulletin No. 26. Forest Research Institute Malaysia, Kepong.

Luostarinen K & Möttönen V. 2004. Effect of growing site, sampling date, wood location in trunk and drying method on concentration of soluble proanthocyanidis in *Betula pendula* wood with special reference to wood colour. *Scandinavian Journal of Forests Research* 19: 234–240.

Milota MR. 1996. Method of measurement of bow and crook. *Forest Products Journal* 41: 65–68.

Mononen K, Alvila L & Pakkanen TT. 2002. CIEL*a*b* measurements to determine the role of felling season, log storage and kiln drying on coloration of silver birch wood. *Scandinavian Journal of Forest Research* 17: 179–191.

Möttönen V. 2006. Variation in drying behavior and final moisture content of wood during conventional low temperature drying and vacuum drying of *Betula pendula* timber. *Drying Technology* 24: 1405–1413.

Moya R, Aguilar D, Tenorio C & Bond B. 2011. Variation of moisture content in kiln dried plantation grown lumber of *Vochysia guatemalensis. Wood and Fiber Science* 43: 121–129.

Moya R & Berrocal A. 2010. Wood colour variation in sapwood and heartwood of young trees of *Tectona grandis* and its relationship with plantation characteristics, site, and decay resistance. *Annals of Forest Science* 67: 109–118.

Moya R & Muñoz F. 2008. Wet pockets in kiln-dried *Gmelina arborea* lumber. *Journal of Tropical Forest Science* 22: 317–328.

Moya R, Ureña E & Muñoz F. 2008. Modulation of moisture content in conventional kiln of wood from fast-growing tropical species in plantation. Paper AP-7 in *Proceedings 2008 SWST International Annual Convention.* 10–12 November 2008, Concepcion.

Muñoz F & Moya R. 2008. Moisture content variability in kiln-dried *Gmelina arborea* wood: effect of radial position and anatomical features. *Journal of Wood Science* 54: 318–322.

Newaz MS, Kamaluddin M & Manzoor R. 2005. Growth and yield prediction models for hybrid acacia (*A. auriculiformis* & *A. mangium*) grown in the plantations of Bangladesh. *Pakistan Journal of Biological Sciences* 8: 1137–1141.

Nishino Y, Janin G, Chanson B, Detienne P, Gril J & Thibaut B. 1998. Colorimetry of wood specimens from French Guiana. *Journal of Wood Science* 44: 3–8.

NIST (National Institute of Standards and Technology). 2005. *Softwood Lumber Standard: Voluntary Product Standard PS 20–05.* Department of Commerce, Washington DC.

Ofori J & Brentuo B. 2005. Green moisture content, basic density, shrinkage and drying characteristics of the wood of *Cedrela odorata* grown in Ghana. *Journal of Tropical Forest Science* 17: 211–223.

Pérez P, Ananias RA & Hernandez G. 2007. Estudio experimental del secado de renovales de canelo *Drimys winteri. Maderas Ciencia y Tecnología* 9: 59–70.

Phelps JE, McGinnes E, Garrett HE & Cox GS. 1983. Growth-quality evaluation of black walnut wood. Part II. Color analyses of veneer produced on different sites. *Wood and Fiber Science* 15: 177–185.

Piao CH, Teng-Tong TL & Teng T. 2000. Research on the drying of *Acacia mangium* lumber. *China Wood Industry* 14: 16–18.

Qumruzzaman C, Iftekhar S & Mahbubul A. 2005. Effects of age and height variation on physical properties of mangium (*Acacia mangium* Willd) wood. *Australian Forestry* 68: 17–19.

Sahri MH, Thrahim FH & Shukor NA. 1993. Anatomy of *Acacia mangium* grown in Malaysia. *IAWA Journal* 14: 245–251.

Shmulky R & Dahlen J. 2007. Influence of sawing solution and pith location on warp in 2 by 4 lumber sawn from small-diameter loblolly pine stems. *Forest Products Journal* 57: 73–75.

Simpson W. 1991. Properties of wood related to drying. Pp 1–50 in Simpson W (ed) *Dry Kiln Operator's Manual Handbook AH–188.* USDA Forest Service, Madison.

Simpson W. 1999. Drying and control of moisture content and dimensional changes. In *Wood Handbook—Wood as an Engineering Material.* General Technical Report FPL–GTR–113. USDA Forest Service, Madison.

Stamm AJ & Raleigh NC. 1967. Movement of fluids in wood. II. Diffusion. *Wood Science Technology* 1: 205–230.

Taylor A, Gartner B & Morrell J. 2002. Heartwood formation and natural durability: a review. *Wood and Fiber Science* 34: 587–611.

Tenorio C & Moya R. 2011. Kiln drying of *Acacia mangium* Willd wood: considerations of moisture content before and after drying and wet pocket presence. *Drying Technology* 29: 1845–1854.

Ward JC. 1986. The effect of wetwood on lumber drying times and rates: an exploratory evaluation with longitudinal gas permeability. *Wood and Fiber Science* 18: 288–307.

Yamamoto K, Sulaiman O, Kitingan C, Choon L & Nhan N. 2003. Moisture distribution in stems of *Acacia mangium, A. auriculiformis* and hybrid acacia trees. *Japan Agricultural Research Quarterly* 37: 207–212.

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

Zobel BJ & Sprague JR. 1998. *Juvenile Wood in Forest Trees.* Springer Verlag, New York.