SCIENTIA
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Influence of wood anatomy on moisture content, shrinkage and during defects in *Vochysia guatemalensis* Donn Sm.

Influência da anatomia da madeira sobre conteúdo de umidade, retração e efeitos da secagem em *Vochysia guatemalensis* Donn Sm.

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Abstract

Vochysia guatemalensis is a native species widely used in Costa Rica for commercial purposes. When this species is processed into lumber and kiln dried, it develops severe defects and the moisture content is not uniform. This research studies the influence of several wood anatomy characteristics (fiber and ray dimensions, lumen diameter, cell wall thickness, and diameter, frequency and percentage of pores) on moisture content, shrinkage, and drying defects. The results showed that the initial moisture content (*MCi*) averaged 159%, ranging from 98% to 281%. Vessel diameter was the only anatomical feature affecting green moisture content. Moisture content after drying (*MCf*) averaged 13.1%, ranging from 10 to 24%, and was influenced by *MCi* and by the distance from the pith. However, it was not affected by any of the wood anatomical characteristics analyzed. It was found that drying defects, such as warps, checks and splits, were influenced by some anatomical features like vessel frequency and ray height; however, their influence tends to disappear under the effect of other variables such as distance from pith and *MCf*.

Keywords: warps drying defects, anatomical features, juvenile wood, tropical wood.

Resumo

Vochysia guatemalensis é uma espécie nativa da América Central com grande aceitação nos programas de reflorestamento. No entanto, sua madeira serrada apresenta pouca uniformidade quanto ao teor de umidade e alta incidência de defeitos após a secagem. No presente trabalho, foram determinadas as características anatômicas (comprimento, largura e diâmetro do lume, espessura da parede celular das fibras; diâmetro, freqüência e porcentagem dos vasos; altura, freqüência e número de células dos raios) analisando a influência no teor de umidade, nas contrações e nos defeitos antes e após a secagem. Os resultados demonstraram que o teor de umidade médio da madeira de 159% antes de secagem e a alta variabilidade do diâmetro dos vasos são parâmetros de maior influência sobre o teor de umidade explicando, no entanto, somente 13% da variabilidade. O teor de umidade após a secagem da madeira foi de 13,1% (variação de 10-24%) sendo influenciado pela distância da medula e pelo teor de umidade antes da secagem. As características anatômicas da madeira não afetaram o teor de umidade após a secagem. Os empenamentos, rachaduras, rajadas, reventaduras e contrações foram pouco afetadas pelas características anatômicas da madeira, sendo que esta influencia tende a desaparecer pela posição da tábua em relação à medula e ao teor de umidade após a secagem.

Palavras-chave: empenamentos, elementos anatômicos, madeira tropical, madeira juvenil.

INTRODUCTION

Wood drying is a relevant treatment during processing, which improves wood properties such as dimensional stability, ability to receive coatings, adhesive compatibility and mechanical properties. In addition, drying improves workability, acoustic properties, and resistance to conduct electricity, as well as the resistance to biodegradation (GU *et al.*, 2004). Proper drying procedures reduce drying defects and ensure uniform moisture content in the final product (GU *et al.*, 2004; SIMPSON, 1999). High variability of final moisture content (*MCf*) in lumber may lead to defects that decrease lumber value (CAI; HAYASHI 2007), and may reduce wood mechanical properties (GU *et al.*, 2004).

The literature suggests that the variation in *MCf* in lumber may be related to wood species (MÖTTÖNEN, 2006), wood extractives (BURTIN *et al.*, 1998; Keey, 2005), tree age (QUMRUZZAMAN *et al.*, 2004), initial moisture content

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(MOYA; MUÑOZ, 2008; OFORI; BRENTUO, 2005), drying schedules (GU *et al*., 2004), heartwood/sapwood presence (YAMAMOTO *et al*. 2003), wood anatomy (MOYA; MUÑOZ, 2008), provenance (LUOSTARINEN; MÖTTÖNEN, 2004, GU *et al*., 2004), and harvesting season (MÖTTÖNEN, 2006).

Some lumber defects, such as warping, checking, or splitting are produced even during sawing (ARCHER, 1986), and they can be increased or reduced during drying (SIMPSON, 1991). This condition could be associated to the drying method (KLAIBER; SEELING, 2004), schedules (MILOTA, 1992), presence of juvenile wood (ZOBEL; SPRAGUE, 1998), and growth stresses in the tree (ARCHER, 1986). Studies about the effect of anatomical features on drying defects development are limited in tropical species (MUÑOZ; MOYA, 2008).

Vochysia guatemalensis Donn Sm. (Vochysiaceae) is an important native species used in plantations in Costa Rica. It has high growth productivity. This species has the ability to grow in sites with low fertility and it is utilized in agroforestry and other silvicultural systems (CALVO-ALVARADO *et al*., 2007). However, V guatemalensis lumber obtained from thinnings and clear-cuttings of fast-growth plantations develops severe drying defects and the moisture content of the final product is not uniform (MOYA *et al*., 2008). Studies to address these problems are needed.

Information explaining the causes for the variations of initial moisture content (*MCi*) and drying defects in *V. guatemalensis* lumber after kiln drying are scarce. For example, Moya *et al*. (2011) reported an average *MCi* of 150%, ranging from 98 to 281% for 8 years old trees from plantations. Additionally, Moya *et al*. (2008) determined that defects like twists, crooks, bows, cups, splits and honeycombs were present in the lumber before kiln drying, and that these defects worsened after drying.

Research about the development of drying defects influenced or caused by wood anatomy is scarce. Some authors have studied the antomical variation of wood of *V. guatemalensis* (BUTTERFIELD *et al*. 1993, GONZALEZ; FISHER, 1998), but not the effects of anatomical features on *MCi* , *MCf* and drying defects. This research analyzed the influence of some anatomical characteristics (fiber dimensions, lumen diameter, cell-wall thickness, vessel tangential diameter, vessel frequency and vessel percentage, ray frequency, ray cell dimensions, number of cells in a ray, and ray width) on the initial and final moisture content variation, shrinkage, and the incidence of defects in green and dried wood of *V. guatemalensis*.

MATERIAL AND METHODS

Tree selection: Twenty *V. guatemalensis* trees were harvested from two 8-year-old plantations in two different climates, ten trees from each origin. One plantation was located on a dry tropical climate region in Northern Costa Rica and the second plantation was located in a wet tropical climate area. Information about the plantations can be found in Aguilar *et al*. (2009) and Moya *et al*. (2011). Ten trees were harvested from a second thinning from each origin. The trees had straight stems with normal branching. The north orientation was marked on each tree. From each tree, two 2.5 m logs were obtained, one at the tree base (lower log) and one between 2.5 to 5.0 m height (upper log). The logs were transported and rapidly processed in a sawmill.

Sawing pattern: The logs were sawn using the pattern in Fig. 1a. 176 boards 2.5 cm thick were cut. Before sawing the logs, the diameter from north to south was measured and marked. After the sawing process, the boards were edged (Figure 1a). When removing each board from the log, the distance from the pith (DP) was measured to establish board location with regard to log radius (relative distance). Each board was identified according to its origin, log position, its DP, and tree number.

Moisture content determination: *MCi* and *MCf* were measured in all boards following ASTM D4442-92 standard (ASTM, 2003). *MCi* was determined from small blocks 2.0 cm by 2.0 cm and 5 mm thick cut at a distance of 27 cm from the lower end of each board (Figure 1b). All boards were 2.15 m long. After drying, another sample was cut to determine *MCf* from the end of each board (Figure 1c).

Drying process: a conventional kiln drying method was used in this study. The drying process was done using an electrically-heated NARDI® pilot kiln with 2 m3 capacity. Two drying schedules were tested and are described in Aguilar *et al*. (2009). Two kiln drying schedules were used to dry the lumber to 12% MC. "A" is referred to as schedule T2-D4 (Table 1) proposed by Boone *et al*. (1988) and this schedule is suitable for wood from natural forests. The second schedule (Table 1) used higher equilibrium moisture contents in all drying steps. It is slower than schedule T2-D4, which is a modification of that program.

Specimen preparation and mensuration of anatomical analysis: small blocks 1.0 cm by 1.0 cm by 1.2 cm. were taken from the MC determination samples and used for anatomical studies. Macerations were prepared using Franklin's method (glacial acetic acid and hydrogen peroxide 1:1 v/v) to measure fiber dimensions (RUZIN, 1999). Permanent slides were mounted following Johansen and Sass's methodology (RUZIN, 1999). An OLYMPUS® light microscope was used to study the anatomical elements and a digital camera was used to photograph the sections. The images were analyzed using IMAGE TOOL® software. The measurements of anatomical elements were repeated 50 times. The measurements

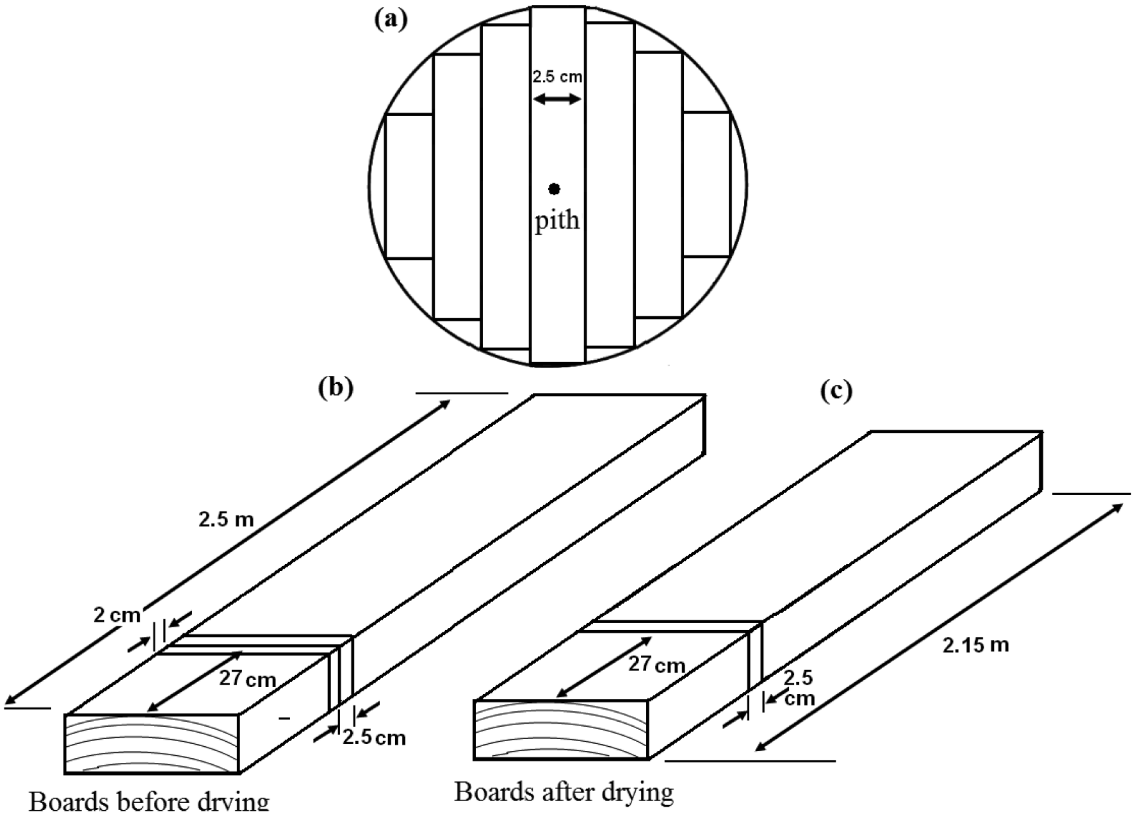


Figure 1. Diagram of the sawing pattern used to cut the logs showing the location of each board (a). Diagrams showing the location of the initial (b) and final (c) moisture content sample.
Figura 1. Padrão de corte usado nas toras, amostrando a localização das tabuas em relação à medula (a). Corte das amostras na determinação de teor de umidade antes (b) e após a secagem (c).

Table 1. Kiln schedules used for drying *Vochysia guatemalensis*.
Tabela 1. Programas de secagem usados na secagem de *Vochysia guatemalensis*.

Step	Schedule T2-D4*			Schedule T2-D4 modified		
	Td (ºC)	EMC (%)	RH (%)	Td (ºC)	EMC (%)	RH (%)
Heating	35	14.8	-	35	18.0	-
Drying	38	14.3	50	38	17.0	82
	38	11.9	45	38	15.0	79
	38	11.9	35	38	13.0	74
	43	10.5	30	44	11.0	69
	44	7.6	30	44	9.0	55
	49	5.5	25	49	7.0	42
	55	4.0	20	55	5.0	31
	66	3.2	15	66	3.2	21
	66	3.2	12	66	3.2	21
Equalization	66	3.2	12	66	3.2	21
Conditioning	60	3.5	-	60	3.5	-
Cooling	30	3.5	-	30	3.5	-

*Dryings schedules from Boone *et al*. (1988).
Legend: Td= Dry-bulb temperature, EMC= equilibrium moisture content, RH=relative humidity.

included: ray height (RH), cells in ray height (CRH), ray width (RW) and cells in ray width (CRW), fiber length (FL), fiber diameter (FØ), lumen diameter (LØ), cell-wall thickness (CW) (obtained by subtracting LØ from FØ), vessel tangential diameter (VTØ), vessel frequency (VF) and percentage of multiples pores (VMP). Both, vessel frequency and percentage of multiple pores were expressed as pores per square millimeter, and ray frequency (RF) was expressed as rays per millimeter.

Drying defects evaluation: each board was evaluated before (green condition) and after kiln drying to determine the presence of defects such as warping (bow, crook, twist and cup), surface checks, and splits. The method suggested by Hallock and Malcolm (1972) and Milota (1996) was used to evaluate drying defects. The boards were measured for maximum crook, bow, and twist on a flat table. The following procedure was used for warp measurement: 1) each piece was positioned on a flat table to examine the extent of each warp type. 2) When the warp was so small that a meaningful determination seemed insignificant, a judgment of "no warp" was assigned. 3) When a warp was present a measurement was made via the insertion of a calibrated wedge. With the wedge inserted to a point of mild refusal, the measurement was made by reading the calibrated vertical face of the wedge. This methodology has been used successfully by Shmulsky and Dahlen (2007).

Drying defects values were reported as: 1) magnitude of the defect in mm in green condition and after kiln drying, 2) the number of boards with defects in relation to the total (percentage of incidence), and 3) defect difference, this is the difference in magnitude of the defect before drying (green condition) versus the magnitude of the same defect after drying. The defect difference was divided in 3 categories: (i) increasing of defects, (ii) defect reduction and (iii) defect equality, this is, the defect did not increase or decrease after drying.

Board shrinkage: shrinkage occurs in the radial, tangential and longitudinal direction: Shrinkage was measured in the width direction as well as in the thickness of each board. The dimension in width and thickness were measured under green and dry conditions. Shrinkage was calculated by the difference in magnitude between green and dry dimensions, and reported as percentage of the dried-dimension.

Statistical analysis: first the effect of anatomical features on MC and drying defects by Pearson correlation analysis was evaluated, which measure the correlation (linear dependence) between independent random variables and dependent variables. This is widely used in science as a measure of the strength of linear dependence between two variables. The Pearson correlation analysis was used to determine which of the anatomical features selected were significantly related to *MCi*, *MCf* and drying defects. The following variables were selected for the correlation: FL, FØ, LØ, CW, VTØ, VF, VMP, RF, RH, CRH, RW and CRW. In addition, a multiple regression (forward stepwise analysis) was carried out to define the main anatomical features affecting *MCi*, *MCf* and drying defects. SAS and STATISTIC 6.0 software were used for the analysis.

RESULTS AND DISCUSSION

Initial moisture content

The average *MCi* was 159%, ranging from 98 to 281%. This result is similar to that found in previous studies (MOYA *et al.*, 2008, MOYA; MUÑOZ, 2010). Moya *et al.* (2008) reported an average of 177% for *MCi* ranging from 160 to 192% for *V. guatemalensis* obtained from 10 year-old plantation trees. Also, Moya and Muñoz (2010) found an average of 146% in *MCi*, ranging from 140 to 160% for boards obtained from 8 year-old plantation trees. High values of *MCi* have been reported for species closely related to *V. guatemalensis* (SG=0.32) with specify gravity (SG) growing in plantations in tropical areas. For example, for *Gmelina arborea* (SG=0.40), the *MCi* found was 170%, ranging from 144 to 181% (MUÑOZ; MOYA 2008). For *Hyeronima alchorneoides* (SG= 0.48), *MCi* was reported to be 111%, ranging from 95 to 120% (Moya *et al.*, 2009). The results reported in these species and the values found in *V. guatemalensis* suggest that high *MCi* is typical for green wood of many species.

Figure 2a shows the frequency distribution of *MCi* for all boards, ranging from 106 to 182%; however some of them have a *MCi* higher than 197%, which is considered high for *V. guatemalensis*. The presence of juvenile wood in *V. guatemalensis* may have caused high *MCi*. Juvenile wood, with thinner cell walls and larger lumens (ZOBEL; SPRAGUE 1998), leads to higher *MCi*.

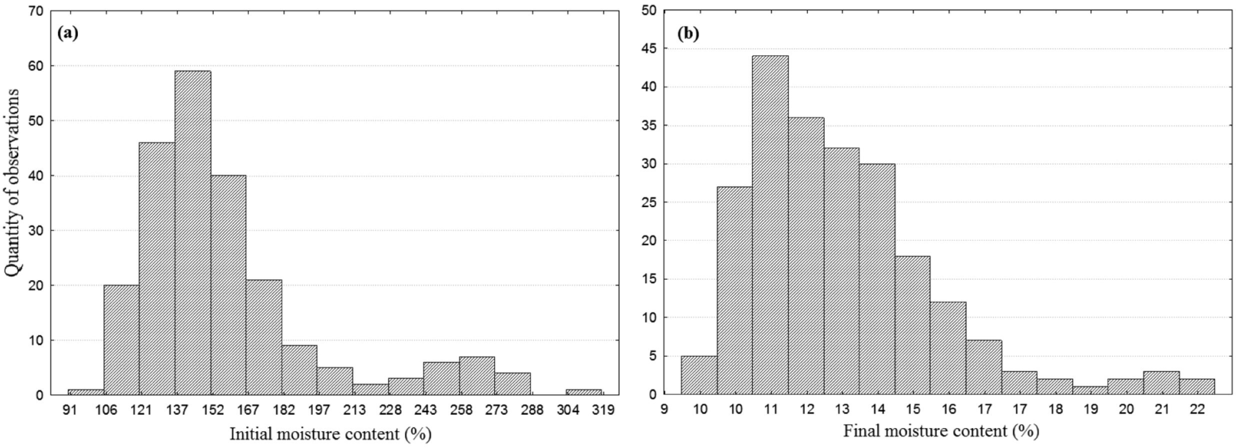


Figure 2. Frequency distribution of MCi (a) and MCf (b) in boards of *V. guatemalensis*.
Figura 2. Distribuição de frequência do teor de umidade antes (a) e após a secagem (b) em madeira de *V. guatemalensis*.

Variables such as DP, CW, VTØ and RH affect *MCi* negatively, while VF affect it positively (Table 2). Regression analysis showed that VTØ was the only anatomical feature affecting *MCi*, however correlation coefficient was low, R2=13%. The effect of anatomical features such as CW, RH and VF, and DP on *MCi* disappeared when a forward stepwise regression analysis was performed (Table 3). The relationship between *MCi* and DP was demonstrated for tropical species such as *Gmelina arborea* and Cedrela odorata. For example, Muñoz and Moya (2008) and Ofori and Brentuo (2005) found a positive correlation between *MCi* and DP for *Gmelina arborea* and Cedrela odorata respectively. However, these authors did not analyze the effect of wood anatomy features on *MCi*.

V. guatemalensis trees increase FL and VTØ from pith to bark, but VF decreases in the same direction (BUTTERFIELD *et al.* 1993, GONZÁLEZ; FISHER 1998). These relationships can explain why *MCi* decreases from pith to bark (PD), and this is probably because void spaces (FL and VF decrease also from pith to bark, and CW, RH and VTØ increase in the same direction.

Final moisture content

The desired *MCf* was 12% for both schedules. The total drying time was 150 hours for T2-D4 schedule and 227 hours for T2-D4 modified schedule. The average *MCf* for all boards was 13.1%, ranging from 10 to 24%. Most of the boards have a *MCf* between 10 to 16% (Fig. 2b). This result showed that *V. guatemalensis* does not achieve uniform moisture content. This result agrees with previous studies in other tropical species (MOYA *et al.*, 2008). Similar findings were also reported for *Gmelina arborea* (MUÑOZ; MOYA 2008) and *Acacia mangium* (TENORIO; MOYA 2011). A high variation in *MCf* suggests that drying was not complete and it is considered not satisfactory for future use of lumber (FPL, 1999). This variation must be minimized to obtain homogenous moisture content in the final product (GU *et al.*, 2004). A variation of ±1% in *MCf* is considered satisfactory for lumber drying (FPL, 1999) and manufactured wood products (SIMPSON, 1999). This study found that boards of *V. guatemalensis* from plantation present a high variation on the *MCf*, therefore, more research is needed to find a solution to this problem.

The analysis of variance (ANOVA) showed that both the *MCi* and the *MCf* were negatively affected by DP and by VTØ, and positively affected by VF (Table 1). Nevertheless, forward stepwise regression analysis showed that *MCf* was significantly affected by DP but not in the case of *MCi* (Table 3). Thus, DP is the most important variable affecting the *MCf* of boards of *V. guatemalensis*. These results are similar to those found in *G. arborea*, in which the *MCf* was negatively affected by DP, FL and RW. However, the *MCf* was positively affected by LØ (MOYA; MUÑOZ 2008). These results differed from the present study because DP was the most important variable affecting *MCf*.

Drying defects

Green boards of *V. guatemalensis* had defects such as warping (twist, crook, bow and cup), checks and splits. The most common were bows and splits, with 88% and 45%, respectively (Fig. 3a). Cup was not observed in green boards, but this defect appeared (high percentage) during drying (Figure 3a). The incidence of twist, crook, cup, checks and honeycomb increased after drying (Figure 3a). However, bow was reduced during drying, and the incidence of splits did not change during drying (Figure 3a).

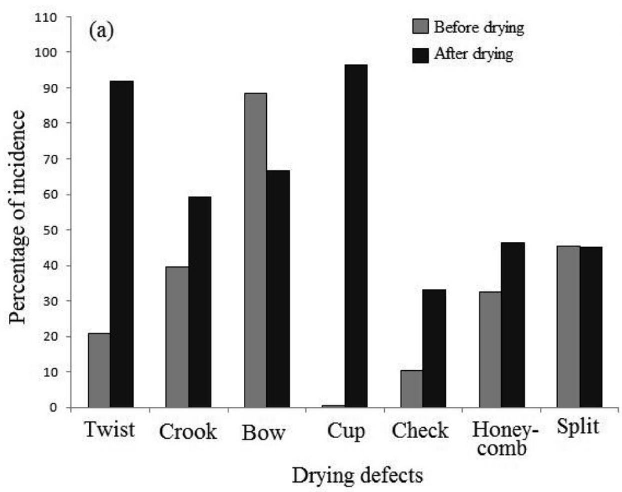
Moya *et al.* (2008) studied drying defects in lumber of *V. guatemalensis* from 10-year-old trees, and the results were similar. They found that bow and crook were the defects with the highest incidence, and cup developed in all boards after drying. Drying defects are common in fast growing species in tropical areas, such as *G. arborea* (MOYA; MUÑOZ 2008), and *A. mangium* (TENORIO; MOYA 2011).

The evaluation of incidence of defects showed that: i) the incidence of splits was not altered after drying (Figure 3b); ii) 54-64% of the boards did not develop checks or honeycomb during drying; in fact these defects were reduced to 35-40% (Figure 3b); iii) the incidence of cup increased in all boards (Figure 3b); iv) 58% of the boards developed bow, but in some boards this defect was reduced to 30% (Figure 3b); v) 60% of the boards did not develop crook during drying, and 35% of them developed it (Figure 3b); vi) 90% of the boards did not develop twist during drying (Figure 3b). According to these results, the drying process affected in different ways the drying defects, in some cases the incidence decreased, as for twists, but in other ones it increased, as for cups.

For other plantation species these observations are similar to our results. Ikami *et al.* (2009) studied the influence of pith location on warping in Cryptomeria japonica, and it was found that bow incidence decreased with drying; while crook incidence was not altered during drying. Moya *et al.* (2008) studied 10 species (*Acacia mangium*, *Alnus acuminata*, *Bombacopsis quinata*, *Cupressus lusitanica*, *Gmelina arborea*, *Swietenia macrophylla*, *Tectona grandis*, *Terminalia amazonica*, *Terminalia oblonga* and *V. guatemalensis*) and found that cup incidence increased during drying in all 10 species. On the other hand, twist and bow incidence decreased with drying, and crook incidence was not altered.

ANOVA results showed that MC affected positively the incidence of honeycomb and splits. On the other hand, *MCf* affected positively the incidence of twist. It was found that *MCf* affected cup negatively during drying (Table 3). DP was positively correlated with almost all drying defects, with the exception of crook and cup (Table 2). In relation to wood anatomy features, it was observed that FL, FØ and LØ were not correlated with any of the drying defects considered in this study (Table 3). However, VTØ, VF and RH were the most important wood anatomical features associated with drying defects. Thus, VTØ was positively correlated with the presence of bow in green boards, and negatively correlated with the presence of honeycomb in green condition as well as after drying (Table 2). VF was positively correlated with the presence of twists and crook in green boards, and with the developing of crook, honeycomb, and twist during drying. RH was positively correlated with twist development during drying, and negatively correlated with the difference of this defect. RH was negatively correlated with the development of honeycomb in green and dried boards (Table 2).

ANOVA results showed that *MCf* and DP (at pith location) were the most important factors on the development of drying defects, and they were more significant than the wood anatomical features studied (Table 3). However, some anatomical characteristics, such as RF, RW, VMF and VF contributed only with a small percent (3.4%) to the development of drying defects (crook, bow, cup and checking) (Table 3).



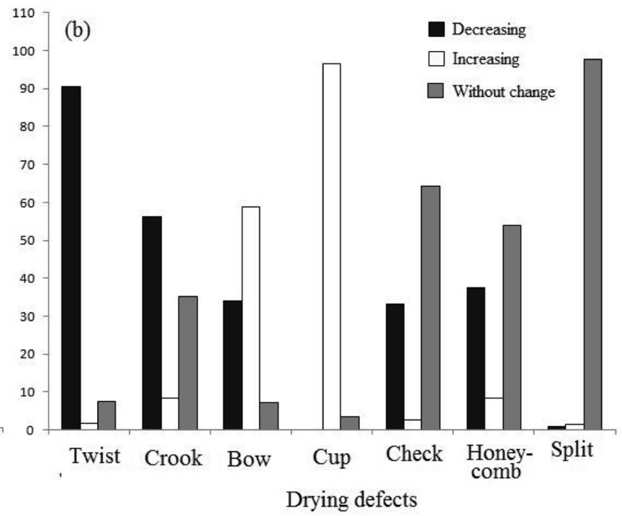


Figure 3. a) Percentage of defects on green and dried boards (before and after drying) of *V. guatemalensis*. b) shows reduction, increment, and absence of change in the percentage of defects during drying.
Figura 3. (a) Porcentagem de defeitos em madeira úmida e seca de *V. guatemalensis*. (b) Redução, incrementos e ausência de modificação na porcentagem de defeitos durante a secagem.

Table 2. Correlation of wood anatomy characteristics of *V. guatemalensis* with moisture content (initial and final) and drying defects (n=167).
Tabela 2. Correlação das características anatômicas de *V. guatemalensis* com o teor de umidade (antes e após a secagem) e defeitos de secagem (n=167).

Factor		MCi	MCf	DP	FL	FØ,	LØ	CW	VTØ	VF	VMP	RF	RW	RH	CRW
DP		-0.21**	-0.48**	-	-	-	-	-	0.48**	-	-0.16*	-	-	0.37**	-
MC	Initial	-	-	-0.21**	-	-	-	-0.20**	-0.38**	0.17*	-	-	-	-0.20*	-
	Final	0.22**	-	-0.48**	-	-	-	-	-0.26**	0.16*	-	-	-	-	-
Twist	Before	-	0.18*	-	-	-	-	-	-	0.17*	-	-	-	-	-
	After	-	-	0.22**	-	-	-	-	-	-	-	-	-	0.24**	-
	Difference	-	-	-0.23**	-	-	-	-	-	-	-	-	-	-0.26**	0.15*
Crook	Before	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	After	-	-	-	-	-	-	-	-	0.16*	-	-	-	-	-
	Difference	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bow	Before	-	-0.48**	0.25**	-	-	-	-	0.17*	-	-	-	-	-	-
	After	-	-	-	-	-	-	-	-	-	0.17*	-	-	-	-
	Difference	-	-	-	-	-	-	-	-	-	-0.17*	-	-	-	-
Cup	Before	-	-	-	-	-	-	-	-	-	-	-0.18*	-	-	-
	After	-	-0.20*	-	-	-	-	-	-	-	-	-	-	-	-
	Difference	-	0.18*	-	-	-	-	-	-	-	-	-	-	-	-
Check	Before	-	-	-0.21**	-	-	-	-	-	-	-	-	0.17*	-	-
	After	-	-	-0.17*	-	-	-	-	-	-	-	-	-	-	-
	Difference	-	-	-	-	-	-	-	-	-	-	-	0.18*	-	-
Honey-comb	Before	0.21**	-	-0.32**	-	-	-	-	-0.21**		-	-	-	-0.20**	-
	After	0.29**	0.28**	-0.38**	-	-	-	-	-0.33**	0.18*	-	-	-	-0.18*	-
	Difference	-	-0.16*	-	-	-	-	-	-	-	-	-	-	-	-
Split	Before	0.23**	0.32**	-0.33**	-	-	-	-0.16*	-	-	-	-	-	-	-
	After	-	0.29**	-0.27**	-	-	-	-	-	-	-	-	-	-	-
	Difference	0.27**	-	-0.18*	-	-	-	-	-	-	-	-	-	-	-
Shrink-age	Width	-	-	-	-	-	-	-	0.19*	-0.16*	-	-	-	-	-
	Thick	-	-	-0.31**	-	-	-	-	-	-	-	-	-	-	-

Legend: MCi = Initial moisture content, MCf = Final moisture content, DP=Distance from the pith, FL= fiber length, FØ= fiber diameter, LØ = lumen diameter, CW=cell-wall thickness, VTØ=vessel tangential diameter, VF=vessel frequency, VMP= percentage of pore multiple, RF=rays frequency, RH=ray height, CRH=cells in ray height, RW=ray width, CRW= cells in ray width, *= statistically significant at 95% confidence , **= statistically significant at 99% confidence .

Table 3. Regression analysis coefficient (forward stepwise) of data obtained from measurements of wood anatomy characteristics of *V. guatemalensis* and their influence on moisture content (initial and final) and drying defects.
Tabela 3. Coeficientes de regressão dos dados obtidos nas medições das características anatômicas de *V. guatemalensis* e sua influencia sobre o teor de umidade (antes e após a secagem) e defeitos de secagem.

Factor		Variable		
		1	2	3
MC	MCi (r=0.41)	VTØ** (r^2=0.13)	CW (r^2=0.01)	-
	MCf (r=0.49)	DP** (r^2=0.229)	MCi (r^2=0.01)	-
Twist	Before (r=0.22)	MCf ** (r^2=0.03)	VF (r^2=0.02)	-
	After (r=0.24)	DP** (r^2=0.05)	RH (r^2=0.01)	-
	Difference (r=0.30)	DP** (r^2=0.06)	CRW (r^2=0.02)	RH (r^2=0.01)
Crook	Before	-	-	-
	After (r=0.11)	VF (r^2=0.01)	-	-
	Difference	-	-	-
Bow	Before (r=0.47)	MCf ** (r^2=0.22)	-	-
	After (r=0.16)	VMP ** (r^2=0.02)	-	-
	Difference (r=0.23)	VMP ** (r^2=0.03)	-	-
Cup	Before (r=0.14)	RF** (r^2=0.02)	-	-
	After (r=0.21)	MCf ** (r^2=0.04)	-	-
	Difference (r=0.20)	MCf ** (r^2=0.04)	-	-
Checks	Before(r=0.26)	DP** (r^2=0.04)	RW** (r^2=0.03)	-
	After (r=0.19)	DP** (r^2=0.03)	-	-
	Difference (r=0.18)	RW** (r^2=0.03)	-	-
Honeycomb	Before (r=0.36)	DP** (r^2=0.108)	MCi ** (r^2=0.02)	-
	After (r=0.45)	DP** (r^2=0.146)	MCi ** (r^2=0.04)	MCf (r^2=0.01)
	Difference (r=0.16)	MCf ** (r^2=0.026)	-	-
Split	Before (r=0.30)	MCf ** (r^2=0.07)	DP** (r^2=0.0)	-
	After (r=0.26)	MCf ** (r^2=0.05)	DP (r^2=0.0)	-
	Difference (r=0.24)	MC i ** |(r^2=0.04)	DP** (r^2=0.02)	-
Shrinkage	Width (r=0.30)	VTØ** (r^2=0.04)	VF (r^2=0.01)	-
	Thick (r=0.37)	DP** (r^2=0.14)	-	-

Legend: MCi = Initial moisture content, MCf = Final moisture content, DP=Distance from the pith, CW=cell-wall thickness, VTØ=vessel tangential diameter, VF=vessel frequency, RH=ray height, RW=ray width, *= statistically significant at 95% confidence, **= statistically significant at 99% confidence.

The high incidence of drying defects can be due to poor properties of juvenile wood of *V. guatemalensis*, making it susceptible to develop drying defects and this was especially true in lumber from small diameter trees. Juvenile wood proportions, growth stress, high radial and tangential shrinkage and high spiral grain in the S2 layer of cell wall contribute to develop drying defects (SIMPSON, 1991; ZOBEL 1984; ZOBEL; SPRAGUE, 1998). Thus, lumber from juvenile trees of *V. guatemalensis* analyzed in this study, could have been influenced by those factors.

Thickness and width shrinkage

Shrinkage values for boards of *V. guatemalensis* averaged 7.87% (0-15%) in thickness and 5.80% (0-27%) in width. Shrinkage in both directions was negatively correlated with VF, while shrinkage in the width direction was positively affected by VTØ (Table 1). However, regression analysis (forward stepwise) showed that VTØ and VF are important wood anatomical features influencing shrinkage in the width direction (Table 2). On the other hand, shrinkage in the thickness direction was not affected by any of the wood anatomical features considered in this analysis.

Wood shrinkage is affected by cell width, wall thickness, frequency and vessel diameter (SIMPSON, 1991), and these anatomical features vary from pith to bark (BUTTERFIELD *et al*., 1993, GONZÁLEZ; FISHER, 1998). However, in boards of *V. guatemalensis*, these relationships were not found. As mentioned earlier, lumber containing juvenile wood, with high spiral grain in the S2 layer of cell wall (SIMPSON, 1991; ZOBEL, 1984; ZOBEL; SPRAGUE, 1998), presents greater values of shrinkage in all directions and these probably were influenced by the shrinkage of the boards (BOWYER *et al*., 2007).

CONCLUSIONS

Initial moisture content of *V. guatemalensis* ranged from 98 to 281%, and averaged 159%. This moisture content was negatively correlated with cell wall thickness, vessel tangential diameter, ray height, and the distance from the pith. Conversely, *MCi* was positively correlated with vessel frequency. However, the regression analysis showed that the vessel tangential diameter affected *MCi* ($P<0.05$) lightly and it was a unique wood anatomy feature that affected the *MCi* in the boards.

The *MCf* averaged 13.1%, ranging from 10 to 24%. This result demonstrates the difficulty to obtain a uniform moisture content when drying *V. guatemalensis*. ANOVA results showed that the board's dry moisture content was negatively affected by the distance from the pith and by vessel tangential diameter. Meanwhile *MCi* and VF were affected positively by *MCf*. However, stepwise forward regression showed that *MCf* was significantly affected by DP.

Warping (twist, crook, bow and cup), checks, honeycomb and splits were the most common defects developed during drying. These defects were significantly correlated with a few wood anatomy features. Pearson correlation analysis showed that ray dimensions (height and width) and their frequency, and vessel frequency were significantly correlated to some drying defects. However, the influence of these wood anatomical features took a second place in comparison with the influence of distance from the pith or juvenile wood in sampled trees.

It was found that shrinkage in the width direction was negatively correlated with vessel frequency, and positively correlated with vessel tangential diameter. On the other hand, shrinkage in the thickness direction was affected positively by VTØ. Pith location was the most important variable on the development of drying defects. Wood anatomy features were responsible for only less than 15% of shrinkage values. Probably other wood properties, such as juvenile wood, can influence these physical properties and perhaps they can take a second place compared to the wood properties evaluated.

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REFERENCES

AGUILAR, D.; MOYA, R.; TENORIO, C. Wood color variation in undried and kiln-dried plantation-grown lumber of *Vochysia guatemalensis*. **Maderas Ciencia y Tecnología**, Concepcion, v.11, n.3, p.207-216, 2009.

ARCHER, R.R. **Growth Stresses and Strains in Trees**. New York: Springer-Verlag, 1986. 240p.

ASTM - American Society for Testing and Materials. ASTM D-4442-92, Standard test methods for direct moisture content measurements of wood and wood-Base materials. **West Conshohocken**, 2003. 22p.

BOWYER, J.L.; SHMULSKY, R.; HAYGREEN, J.G. **Forest products and wood science: An introduction**. 5ed. San Francisco: Wiley-Blackwell, 2007. 353p.

BOONE, R.S.; KOZLIK, C.J., BOIS, P.J.; WENGERT, E.M. **Dry kiln schedules for commercial woods—Temperate and tropical.** Madison: USDA/Forest Service Product Laboratpory, 1988. 158p. (Gen Tech Rep FPL-GTR-57).

BURTIN, P.; JAY-ALLEMAND, C.; CHARPENTIER, J.; JANIN, G. Natural wood colouring process in *Juglans* sp. (*J. regia* and hybrid *J. nigra* 23 x *J. regia*) depends on native phenolic compounds accumulated in the transition zone between sapwood and heartwood. **Trees: structure and function**, Vancouver, v.12, n.5, p.258-264, 1998.

BUTTERFIELD, R.P.; CROOK, R.P.; ADAMS, R.; MORRIS, R. Radial variation in wood specific gravity, fiber lengths and vessel area for two Central American hardwoods: *Hyeronima alchornoides* and *Vochysia guatemalensis* natural and plantation-grown trees. **IAWA Journal**, Leiden, v.14, p.153-162, 1993.

CAI, Y.; HAYASHI, K. New monitoring concept of moisture content distribution in wood during RF/vacuum drying. **Journal of Wood Science**, Tokio, v.53, p.1-4, 2007.

CALVO-ALVARADO, J.C.; ARIAS, D.; RITCHER, D.D. Early growth performance of native and introduced fast growing tree species in wet to sub-humid climates of the Southern region of Costa Rica. **Forest Ecology Management**, Netherlands, v.242, n.2-3, p.227-235, 2007

FPL - FOREST PRODUCTS LABORATORY. **Wood handbook—Wood as an engineering material**. Madison: Forest Products Laboratory, 1999. 750p. (Gen. Tech. Rep. FPL–GTR–113)

GONZÁLEZ, E.; FISHER, R. Variation in selected wood properties of *Vochysia guatemalensis* from four sites in Costa Rica. **Forest Science**, Bethesda, v.44, n.2, p.185-191, 1998.

GU, H.; YOUNG, T.M.; MOSCHLER, W.W.; BOND, B.H. Potential sources of variation that influence the final moisture content of kiln- dried hardwood lumber. **Forest Products Journal**, Madison, v.54, n.11, p.65-70, 2004.

HALLOCK, H.Y.; MALCOLM, F.B. **Sawing to reduce warp in plantation red pine studs.** Madison: USDA/Forest Products Laboratory, 1972. 27p. (Research paper FLP-164)

IKAMI, Y.; MATSUMURA, Y.; TSUCHIKAWA, S. Influence of pith location on warp of lumber in sawing medium-quality sugi (*Cryptomeria japonica* D. Don) logs. **European Journal of Wood and Wood Products**, Munich, v.67, n.3, p.271-276, 2009.

KEEY, R. Colour development on drying. **Maderas Ciencia y Tecnología**, Concepcion, v.7, n.1, p.3-25, 2005.

KLAIBER, V; SEELING, U. The influence of drying method on the warp behavior or Norway spruce (*Picea abies* (L.) Karst.) sawn timber. **Forest Products Journal**, Madison, v.54, n.4, p.79-87, 2004.

LUOSTARINEN, K.; MÖTTÖNEN, V. 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. **Scandian Journal of Forests Research**, Knivsta, v.19, n.3, p.234- 240, 2004.

MILOTA, M.R. Effect of kiln schedule on warp in Douglas-fir lumber. **Forest Products Journal**, Madison, v.42, n.2, p.57-60, 1992.

MILOTA, M.R. Method of measurement of bow and crook. **Forest Products Journal**, Madison, v.41, n.9, p.65–68, 1996.

MÖTTÖNEN, V. Variation in drying behavior and final moisture content of wood during conventional low temperature drying and vacuum drying of *Betula pendula* timber. **Drying Technology**, Philadelphia, v.24, n.11, p.1405–1413, 2006.

MOYA, R.; MUÑOZ, F. Wet pockets in kiln-dried *Gmelina arborea* lumber. **Journal of Tropical Forest Science**, Kepong, v.22, n.3, p.317-328, 2008.

MOYA, R.; MUÑOZ, F. Physical and mechanical properties of eight species growing in fast growth plantations in Costa Rica. **Journal of Tropical Forest Science**, Kepong, v.22, n.3, p.317-328, 2010.

MOYA, R.; AGUILAR, D.; TENORIO, C.; BOND, B. Variation of moisture content in kiln dried plantation grown lumber of *Vochysia guatemalensis*. **Wood Fiber and Science**, Madison, v.43, n.2, p.121-129, 2011.

MOYA, R.; LEANDRO, L.; MURILLO, O. 2009. Wood characteristics of *Terminalia amazonia*, *Vochysia guatemalensis* and *Hyeronima alchorneoides* planted in Costa Rica. **Bosques**, Valdivia, v.30, n.2, p.78-87, 2009.

MOYA R.; URUEÑA E.; MUÑOZ, F. Modulation of moisture content in conventional kiln of wood from fast-growing tropical species in plantation. In: SWST INTERNATIONAL ANNUAL CONVENTION, 2008, Concepcion. **Proceedings**... Madison: Society of Wood Science and Technology, 2008. Paper AP-7, 7p.

MUÑOZ, F.; MOYA, R. Moisture content variability in kiln-dried *Gmelina arborea* wood: effect of radial position and anatomical features. **Journal of Wood Science**, Tokio, v.54, n.4, p.318-322, 2008.

OFORI, J.; BRENTUO, B. Green moisture content, basic density, shrinkage and drying characteristics of the wood of *Cedrela odorata* grown in Ghana. **Journal of Tropical Forest Science**, Kepong, v.17, n.2, p.211–223, 2005.

QUMRUZZAMAN, C.; IFTEKHAR, S.; MAHBUBUL, A. Effects of age and height variation on physical properties of mangium (*Acacia mangium* Willd) wood. **Australian Forestry**, Sidney, v.68, n.1, p.17-19, 2005.

RUZIN, S.E. **Plant Microtechnique and Microscopy**. New York: Oxford University, 1999. 322p.

SIMPSON, W. Properties of wood related to Drying. In: _______. **Dry Kiln Operator's Manual Handbook AH-188**. Madison: Forest Products Laboratory, 1991. p.1-41.

SIMPSON, W. Drying and control of moisture content and dimensional changes. In ______. **Wood Handbook- Wood as an Engineering Material**. Madison, WI: Forest Products Laboratory, 1999. p.56-98. (Gen. Tech. Reo. FPL-GTR-113).

SHMULSKY, R., DAHLEN, J. Influence of sawing solution and pith location on warp in 2 by 4 lumber sawn from small-diameter loblolly pine stems. **Forest Products Journal**, Madison, v.57, n.7/8, p.73-75, 2007.

TENORIO, C.; MOYA, R. Kiln Drying of *Acacia mangium* Willd wood: considerations of moisture content before and after drying and wet pocket. **Drying Technology**, Philadelphia, v.29, n.15, p.1845-1854, 2011.

YAMAMOTO, K.; SULAIMAN, O.; KITINGAN, C.; CHOON, L.; NHAN, N. Moisture distribution in stems of *Acacia mangium*, *A. auriculiformis* and hybrid acacia trees. **Japan Agricultural Research Quarterly**, Tokio, v.37, n.3, p.207-212, 2003.

ZOBEL, B.J. The changing quality of the world wood supply. **Wood Science Technology**, Munich, v.18, n.1, p.1-17, 1984.

ZOBEL, B.; SPRAGUE, S. **Juvenile wood in trees**. New York: Springer-Verlag, 1998. 367p.

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