

WOOD DENSITY VARIATION AND TREE RING DEMARCATION IN *Gmelina arborea* TREES USING X-RAY DENSITOMETRY

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ABSTRACT: Due to its relationship with other properties, wood density is the main wood quality parameter. Modern, accurate methods – such as X-ray densitometry - are applied to determine the spatial distribution of density in wood sections and to evaluate wood quality. The objectives of this study were to determine the influence of growing conditions on wood density variation and tree ring demarcation of *gmelina* trees from fast growing plantations in Costa Rica. The wood density was determined by X-ray densitometry method. Wood samples were cut from *gmelina* trees and were exposed to low X-rays. The radiographic films were developed and scanned using a 256 gray scale with 1000 dpi resolution and the wood density was determined by CRAD and CERD software. The results showed tree-ring boundaries were distinctly delimited in trees growing in site with rainfall lower than 2510 mm/year. It was demonstrated that tree age, climatic conditions and management of plantation affects wood density and its variability. The specific effect of variables on wood density was quantified by for multiple regression method. It was determined that tree year explained 25.8% of the total variation of density and 19.9% were caused by climatic condition where the tree growing. Wood density was less affected by the intensity of forest management with 5.9% of total variation.

Key words: *Gmelina arborea*, tree-rings, X-ray densitometry, wood anatomy.

VARIAÇÃO DA DENSIDADE DA MADEIRA E DEMARCAÇÃO DOS ANÉIS DE CRESCIMENTO DE ÁRVORES DE *Gmelina arborea* PELA DENSITOMETRIA DE RAIOS X

RESUMO: Devido à relação com as outras propriedades, a densidade da madeira é o seu principal parâmetro de qualidade. Métodos modernos e precisos - como a densitometria de raios X - são aplicados para determinar a distribuição espacial da densidade, em seções da madeira e avaliar a sua qualidade. Objetivou-se, neste estudo, determinar a influência das condições de crescimento na variação da densidade da madeira e na demarcação dos anéis de crescimento de árvores de *gmelina*, de plantações de rápido crescimento na Costa Rica. A densidade da madeira foi determinada pelo método de densitometria de raios X. Amostras do lenho foram cortadas de árvores de *gmelina* e expostas à fonte de raios X, de baixa energia. Os filmes radiográficos foram revelados e "escaneados" utilizando-se uma escala de cinza com 1000 dpi de resolução, sendo a densidade da madeira determinada pelos softwares CRAD e CERD. Os resultados mostraram que os limites dos anéis de crescimento foram delimitados distintamente nas árvores com precipitação abaixo de 2510 mm/ano. Demonstrou-se que a idade das árvores, as condições climáticas e o manejo das plantações afetam a densidade da madeira e a sua variabilidade. O efeito específico dessas variáveis na densidade de madeira foi quantificado pela análise de regressão múltipla "forward stepwise". Determinou-se que a idade da árvore explicou 25,8% do total de variação da densidade e que 19,9% dessa variação foi causada pela condição climática do local de crescimento das árvores. A densidade da madeira foi menos afetada pela intensidade de manejo florestal com 5,9% da variação total.

Palavras-chave: *Gmelina arborea*, anéis de crescimento, densitometria de raios X, anatomia da madeira.

1 INTRODUCTION

Gmelina arborea is one of the most important species timber for solid wood production in Costa Rica. Approximately 65 000 hectares planted in different ecological zones of Costa Rica: from wet to dry and under a variety of silvicultural management regimes (MOYA, 2004). Commercial plantations were established in areas with different climatic and soil conditions and several silvicultural management had been applied. However, the effects of the environment, site, and silviculture on wood

density or tree ring formation on wood from *gmelina* are scarce.

Wood density is related to its anatomical, physical-mechanical properties and affects the drying properties of the *gmelina* wood (MUÑOZ & MOYA, 2008; MOYA & MUÑOZ, 2008; MOYA & TOMAZELLO, 2007a,b). Wood density variation occurs across radial direction, along the longitudinal direction of the stem and within the annual rings of the stem (ESPINOZA, 2004; MOYA & TOMAZELLO, 2007a). The variation in wood density may be due to genetic, physiological, or silvicultural treatments

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(MULLER-LANDAU, 2004). On the other hand, variations in width and density of annual rings have been widely applied as estimates of past climatic conditions (FRITTS, 1976). In general, annual increments of tree-growth integrate the effects of daily, weekly, or monthly weather conditions over the entire growing season.

Different methods have been developed to measure wood density variation in annual rings, along or across the stem. However, the X-ray densitometry profile has been used to determine wood density variation (SCHINKER et al., 2003); and also to access more information about wood formation, physiological processes, the amount or proportion of different cell types, and spatial arrangements (KOGA & ZANG, 2004). This method was first introduced to the field of wood analysis by Polge (1963); moreover, it was developed by various researchers (POLGE, 1978).

Wood density variation is essential to select sites and forestry practices, and to predict wood end-uses. This paper was designed to analyze wood density variability in radial orientation and tree ring demarcation in *Gmelina* trees from different climates and different management conditions, using X-ray densitometry.

2 MATERIAL AND METHODS

2.1 Sampled areas

The study was carried out on 30 mature *Gmelina arborea* trees. Nine to twelve year old plantations were sampled in the north and northwest (09° 47' -11° 05' N; 83° 40' -85° 50' E) of Costa Rica (Figure 1). Mean annual precipitation is 3000-5000 mm with an average temperature of 20-25 °C; a moderate drought period of 3 months (January-March) with rainfall decreasing from 450 to 70 mm/month in the north. In the northwest, the mean annual precipitation is 1500-2000 mm with an average temperature of 25-28°C, a severe drought period between January and March whereby rainfall is almost 0 mm/month.

2.2 Silvicultural regimes, plots, and tree selection

From each climatic condition (north and northwest) 15 different plantations were selected with different management intensity: 5 were intensively managed (< 350 trees ha⁻¹), 5 were managed intermediately (350-700 trees ha⁻¹) and 5 were unmanaged (>700 trees ha⁻¹), representing forest management regimes in Costa Rica (Figure 1). Moya & Tomazello (2008) described widely the plantations conditions sampled felled in this study. Nine to twelve

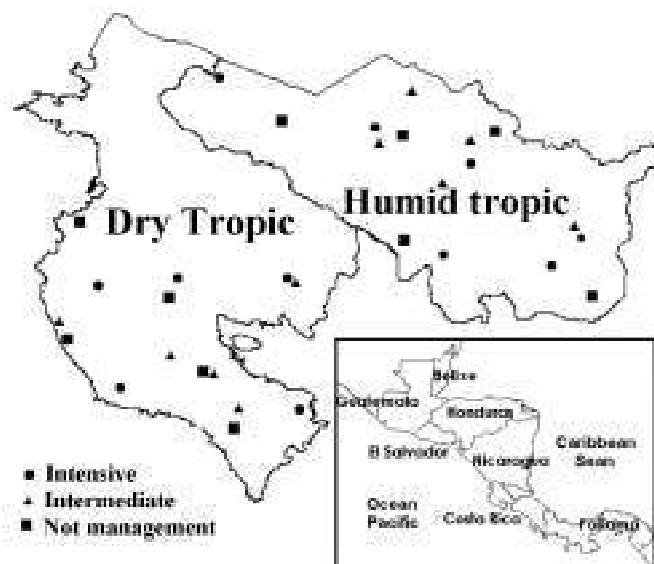


Figure 1 – Location of sampled plantations (● unmanaged, ▲ intermediate and ■ intensively managed) under two climatic conditions (dry and humid) in Costa Rica).

Figura 1 – Localização das plantações amostradas (● sem manejo, ▲ manejo intermédio e ■ manejo intensivo) em duas condições climáticas (seca e úmida) da Costa Rica.

years old trees were sampled and measured. The geographic location was determined by global position system (GPS). Two trees, that had an average DBH, straight trunk, normal branching, and no disease or pest symptoms, was selected from each trial.

2.3 Wood samples and x-ray exposure

Each selected tree was marked on the north facing side; and a stem section (3 cm thickness) was cut at DBH. A slice, 1 cm wide and 2 mm thick, was cut across the diameter (Figure 2). For density determination, samples (1 ± 0.045 mm; mean \pm SD) were cut using a twin-blade saw (Figure 2a). The thin laths at 12% moisture content (MC) were X-rayed on a film using a Hewlett Packard Faxitron (Model 43805 N) previously adjusted (time: 5 minutes; energy: 16 Kv; intensity: 3 mA) (Figure 2b). The films (Kodak, Diagnostic Film X-Omat XK1, 24 x 18 cm) were developed using normal procedures (AMARAL & TOMAZELLO, 1998) and it permitted reconstructed cross section of thin lath of wood and so determined gray value used for correlated with wood density. The radiographs of film of *Gmelina arborea* wood samples were scanned at a 256 gray scale with 1000 dpi resolution.

2.4 Wood density determination, tree-ring boundary and data analysis

Micro-density X-ray measurements (X-ray densitometry) were carried out using CERD software

(MOTHE et al., 1998). The gray values were read on digital radiographs along their length (usually from pith to bark), and converted to density traces (Figure 3). Walker and Dood's method (WALKER & DOBB, 1988) for densitometry profiles was used in the determination of the mean wood density and the intra-ring wood density variation. The density parameter in each growth ring was averaged between the north and south parts of the stem.

The tree ring boundary was determined in density profile. The highest density value was used as boundary between two rings (Figure 3). However, it was difficult to establish in some density profile, especially in wood samples from trees growing in sites with rainfall over 3100 mm/years. Afterwards, with objective to examine the microscopic wood structure, were prepared two permanent slides in area (1 x 1 cm) on tree-ring boundary zone. One area was cut from well distinct tree-ring and other one from less distinct. Thin transversal sections (permanent slides) about 10-15 μ m thick were cut by using a microtome (Leica SM2000R). These sections were stained with safranina and glued with Canada balsam (RUZIN, 1999).

An analysis of variance (ANOVA) was carried out to test the significance of the differences in mean values of the wood density of each annual ring. Climatic conditions and management intensity were independent variables; and the density values were the dependent variables. A contrast test (99% confidence level) was applied to verify the

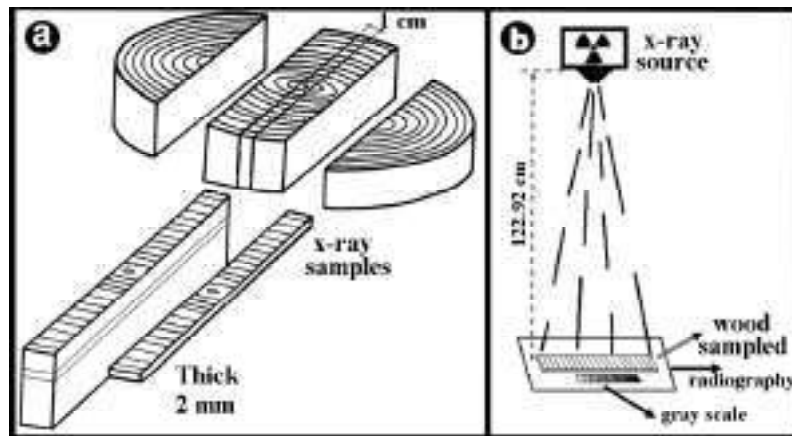


Figure 2 – Thin cross-sections sampled from a stem section of *Gmelina arborea* trees (a) and X-ray exposure conditions (b).

Figura 2 – Seções transversais finas das amostras do lenho de árvores de *Gmelina arborea* (a) e condições de irradiação com raios X (b).

difference between climatic conditions and management treatments for mean annual growth ring.

3 RESULTS AND DISCUSSION

3.1 Tree ring distinctness

Tree ring boundaries were predicted with an intra-ring wood density fluctuation, which reflected rainfall variations too. More distinct tree-rings were seen on gmelina trees grown on sites with less than 3100 mm rainfall/year (Figure 3a and 3b). However, less distinct growth rings were observed in trees from plantation growing in sites with rainfall higher than 3100 mm/year. In fact, tree ring boundaries were marked with great difficulty in some part of cross-sections (Figure 3c and 3d).

Previous research had detailed wood anatomical variations and its effects on wood density of gmelina trees (TEWARI, 1995) or the tree-ring boundary and wood

density (AKACHUKU, 1985). Wood density is primarily a measure of the amount of wood and cell material per unit volume; it is also related to the relative proportions of 4 distinct cell types or tissues in hardwood species (vessel, fiber, axial and radial parenchyma), along with their dimensions and distribution (COWN & PARKER, 1978).

The examinations of microscopic wood structure showed that the distinct and less-distinct tree-rings in gmelina trees encompass some features related to wood anatomy that affect the wood density. The boundaries of the less-distinct tree-rings are made up of latewood with few diffuse vessels and thick wall fibers, and earlywood with little difference in the fibers' wall and distribution and the dimension of vessels (Figure 4a). In the distinct tree-rings, the boundaries are distinctly marked by a band of thicker wall fibers and smaller diameter vessels, followed by the earlywood (vessels with larger diameter are grouped in semi to ring-porous, and fibers with thin and large walls)

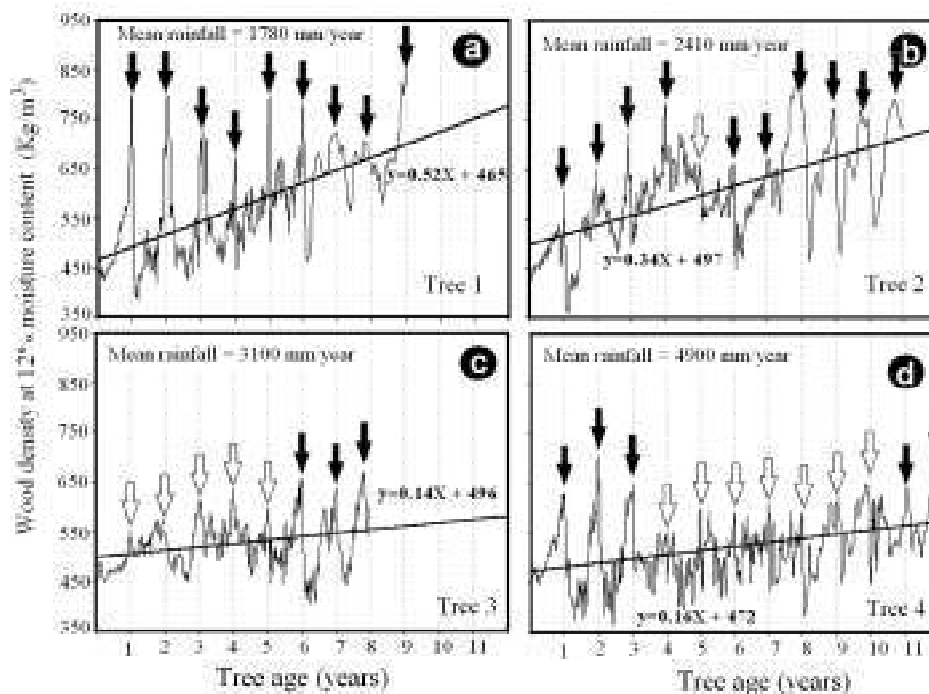


Figure 3 – Radial wood density variation of *Gmelina arborea* trees in different rainfall levels (black arrow shows tree-ring boundary, white arrow shows less distinct tree-ring and black line shows the regression line $y = ax + b$).

Figura 3 – Variação radial da densidade da madeira de árvores de *Gmelina arborea* em diferentes níveis de precipitação (setas negras indicam o limite do anel de crescimento distinto, setas brancas anel de crescimento menos distinto e a linha negra a da regressão $y = ax + b$).

and latewood (vessels diffuse and smaller, and fibers with thick and narrow walls) with a transition phase between early-latewood (Figure 4b).

The effect of rainfall on wood density profiles from pith to bark has shown variations in the behavior of this property. For example, in trees from sites with 2410 mm/year, there was a tendency line and a higher wood density profile with lesser intra annual tree-ring variation (Figure 3b) than in sites with 1780 mm/year of rainfall. However, the climatic effect is more effective and detectable in sites with 3100 (Figure 3c) and 4900 mm/year (Figure 3d); where the tendency line presented across the radial direction was almost horizontal (mean density of 460 Kg m⁻³) and with intra annual tree-ring variations less distinct compared to dryer sites.

In accordance with these results, it was clear that wood density and tree-rings are affected by rainfall. Physiological processes of gmelina trees are seasonally related with cambium, and wood formation is affected by the differences in the water and minerals available (WORBES et al., 1995). According to Dave & Rave (1982), gmelina trees comprise decreasing stomatal conductance and total defoliation affecting photosynthesis and organic sap production during the drought period, reflecting in the meristematic cambium activity. The distinct tree-ring and wood density profile of gmelina trees from dry tropical sites resulted from the restricted and controlled rainfall distribution: the highest wood density values are presented

by trees with distinct tree-rings from dryer sites (Figure 3a) and the lowest wood density values by trees with less-distinct tree rings from highest rainfall levels (Figure 3b).

3.2 Relationships between wood density and climatic and management condition

The wood density ranged from 440 to 687 Kg m⁻³ (Table 1) and was found that density increased with increasing tree age (Figure 5), varying in different way with management and climatic conditions. The average varied from 505 to 622 Kg m⁻³ for dry climatic condition and from 454 to 570 Kg m⁻³ for humid condition. For intensive managed trees the wood density average ranged 497 to 622 Kg m⁻³ and 469 to 548 Kg m⁻³ for dry and humid condition, respectively. The wood density variation was from 533 to 632 Kg m⁻³ for dry climatic and 440 to 549 Kg m⁻³ in trees from plantation with intermediate management. The wood density also varying from 483 to 686 Kg m⁻³ in dry condition and from 454 to 576 Kg m⁻³ in humid climatic condition for not managed gmelina trees (Table 1). Another important point, that may observed in the table 1 is that average values of wood density was statistically higher in trees from dry climatic conditions that density values in trees from humid conditions.

Gmelina wood density values from X-ray radiography showed that the inter tree-ring wood density was significantly affected (at 99% confidence level) by the tree age, the climate (dry or wet tropical) and the management

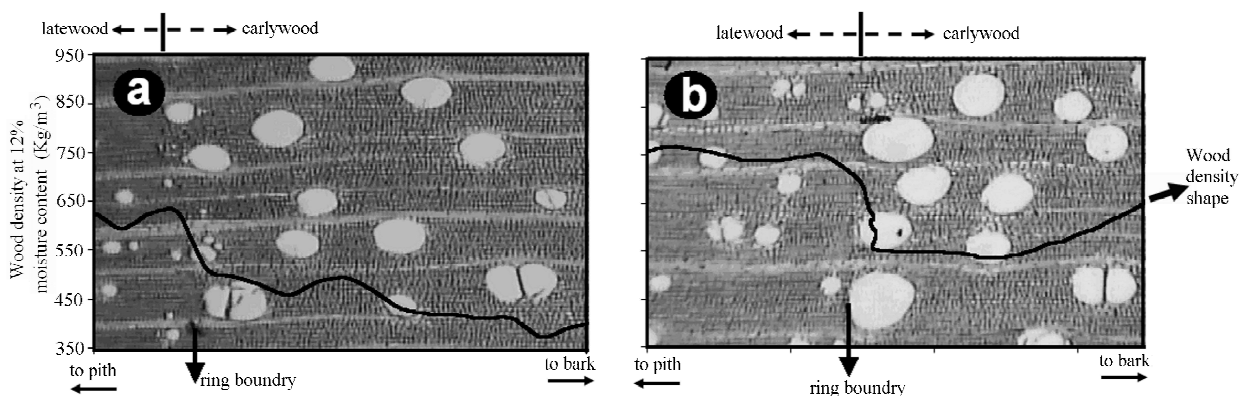


Figure 4 – Wood density variation throughout *Gmelina arborea* tree-rings and related wood anatomical cross-section features: (a) less distinct and (b) distinct tree ring (the black line shows wood density variation within ring boundary).

Figura 4 – Variação da densidade da madeira no anel de crescimento de *Gmelina arborea* e relação com as suas características anatômicas em seção transversal: (a) anel de crescimento menos distinto e (b) anel de crescimento distinto (a linha negra mostra a variação da densidade ao longo do limite do anel).

Table 1 – Wood density values for different tree age in *Gmelina arborea* from different climatic and management conditions in Costa Rica.**Tabela 1** – Valores de densidade da madeira de *Gmelina arborea* de diferentes climas e condições de manejo na Costa Rica.

Tree age (years)	All sampled trees		Intensive		Intermediate		Non management	
	Dry	Humid	Dry	Humid	Dry	Humid	Dry	Humid
1	505 ^A	454 ^B	497 ^A	469 ^A	533 ^A	440 ^B	483 ^A	454 ^B
2	513 ^A	475 ^B	483 ^A	471 ^A	540 ^A	488 ^B	516 ^A	466 ^B
3	541 ^A	495 ^B	512 ^A	482 ^A	585 ^A	525 ^B	526 ^A	478 ^B
4	527 ^A	493 ^B	498 ^A	496 ^A	574 ^A	517 ^B	509 ^A	467 ^B
5	567 ^A	514 ^B	516 ^A	510 ^A	597 ^A	542 ^B	587 ^A	491 ^B
6	579 ^A	514 ^B	562 ^A	518 ^A	593 ^A	536 ^B	581 ^A	489 ^B
7	592 ^A	514 ^B	576 ^A	515 ^B	610 ^A	533 ^B	590 ^A	495 ^B
8	604 ^A	534 ^B	575 ^A	514 ^B	641 ^A	569 ^B	593 ^A	519 ^B
9	629 ^A	518 ^B	590 ^A	515 ^B	687 ^A	521 ^B	634 ^A	522 ^B
10	637 ^A	533 ^B	629 ^A	510 ^B	644 ^A	549 ^B	649 ^A	535 ^B
11	624 ^A	539 ^B	604 ^A	548 ^B	632 ^A		686 ^A	530 ^B
12	622 ^A	570 ^B	622 ^A					570 ^B
Average	578 ^A	513 ^B	555 ^A	504 ^B	603 ^A	522 ^B	578 ^A	501 ^B

Legend: Different letters in the same age and management are statistically different at 99%.

Nota: Letras diferentes na mesma idade no mesmo manejo são estatisticamente diferentes ($\alpha=0,01$).

regimes. The stepwise forward analysis in multiple regression applied to the data indicate that tree age, climate, and management intensity explain 25.8, 19.9, and 5.9% of the total variation of inter tree-ring wood density, respectively (Table 2).

The effect of tree age on wood density observed by several authors (Akachuku & Burley, 1979; Alipon, 1991; Espinosa, 2004; Ohbayashi & Shiokura, 1989; Zeeuw & Gray, 1972), indicated that the wood density increased from 450 to 650 Kg m⁻³ (Figure 5a), representing an increment of 45% of the lowest values (450 Kg m⁻³) to highest values (650 Kg m⁻³). Along with the tree aging, modifications on the woody cells were produced (MOYA & TOMAZELLO, 2007a). The effect of climate on trees was also detected relative to the wood density: in dry sites the density was statistically higher (12.59%) than in wet sites (Figure 5a). The management regimes applied to the gmelina plantations also affected the climatic type; the increase in wood density for dry tropical conditions compared to wet tropical conditions was of 8.89; 15.12 and 16.40% from the intensive, intermediate and not managed trees, respectively.

Moreover, the gmelina tree growth in humid tropical sites produced wood with the lowest intra tree-ring variation regarding wood density. The increment of wood density produced by aging of cambium was less in trees from the wet tropical conditions in all intensity management plantations. The tendency curve has lower values of wood density in wet tropical than density values in dry tropical (Figure 5b-c). The analysis of variance (ANOVA) for each individual year, from the 1st to the 12th year, showed significant difference in all years for the intermediate and the not managed plantations (Figure 5c and 5d) and after the 7th year for the intermediate managed plantations (Figure 5b). The rainfall regime in Costa Rica appears to be an important factor in determining the wood anatomy and density of *Gmelina arborea* trees (MOYA & TOMAZELLO, 2008). This was shown by Villar et al. (1997) in *Quercus sp* trees, whereby the availability of water affects the vessel, fiber, and parenchyma dimensions. The higher wood density value in dry tropical sites resulted in the reduction of vessel percentage and diameter and in the increase of fiber wall thickness in gmelina tree wood (MOYA & TOMAZELLO, 2007a).

Table 2 – Summary of the analysis of variance of regression analyses by forward stepwise for average wood density of *Gmelina arborea* in Costa Rica.

Tabela 2 – Resumo da análise da variância da regressão “forward stepwise” da densidade média da madeira das árvores de *Gmelina arborea* na Costa Rica.

Effect	Estimator	Standard Deviation	Value F	Forward Stepwise	R ²	Change R ²
Intercept**	4514.55	468.45	9.64	-	-	-
Tree age**	12.12	0.71	17.10	1	0.258	0.258
Growing**	60.38	3.98	15.16	2	0.457	0.199
Management**	20.05		8.18	3	0.516	0.059

** Statistically different at 99%.

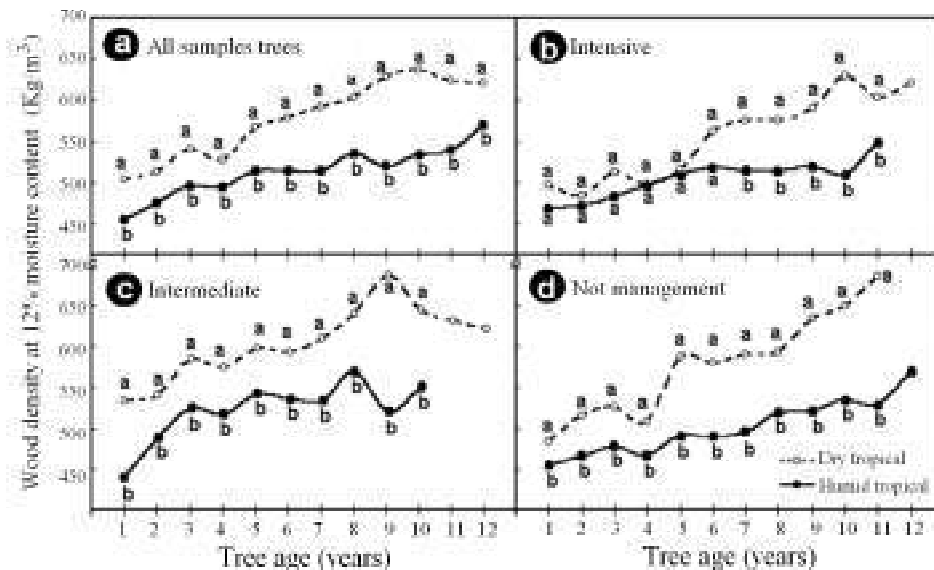


Figure 5 – Wood density variation of *Gmelina arborea* trees from dry and humid tropical climate in Costa Rica: (a) all sampled; (b) intensive; (c) intermediate and (d) not managed plantations. Different letters in the same age are statistically different at 99%.

Figura 5 – Variação da densidade da madeira de árvores de *Gmelina arborea* de clima tropical seco e úmido da Costa Rica: (a) todas as árvores amostradas; (b) manejo intensivo; (c) manejo intermediário e (d) plantações sem manejo. Letras diferentes na mesma idade são estatisticamente diferentes a 99% de confiança.

4 CONCLUSIONS

With X-ray radiation on thin wood samples is possible to establish tree-ring demarcation, intra-ring density variation, and wood density variation from pith to bark of *Gmelina arborea* trees.

Distinct tree-rings were presented in gmelina tree growing on sites with less than 3100 mm rainfall/year. Whereas, sites where rainfall was higher than 3100 mm/year produced trees with less-distinct annual rings.

Wood density values determined from X-ray radiography showed that wood density was affected

significantly by the age of the tree, the climatic conditions (dry or wet tropical) and the management regimes. This wood property increased from pith to bark. Trees from dry tropical conditions produce a larger density than those from dry conditions. But differences found for tree age and climatic conditions can be adjusted by forest management.

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