

EVALUATION OF BIODETERIORATION AND THE  
DYNAMIC MODULUS OF ELASTICITY OF WOOD IN TEN  
FAST-GROWING TROPICAL SPECIES IN COSTA RICA  
EXPOSED TO FIELD TESTING

RÓGER MOYA, ALEXANDER BERROCAL  
INSTITUTO TECNOLÓGICO DE COSTA RICA, ESCUELA DE INGENIERÍA FORESTAL  
CARTAGO, COSTA RICA

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ABSTRACT

In tropical regions, it is possible to produce a large variety of timber species in plantation conditions. However, wood from these trees has low natural durability. Biodeterioration and the dynamic modulus of elasticity of wood ( $d_{MOE}$ ) were evaluated in 10 fast-growing tree species in Costa Rica during a 36-month exposure field test. Results showed a reduction in wood density of up to 50-80 % of the  $d_{MOE}$  in non-treated wood. Treatment with preservatives (Wolmanit CX-10) increased the wood's durability. In all species studied, loss in wood density decreased with absorption of the preservative. In the remaining species, we did not find that absorption of the preservative affected the loss of density or  $d_{MOE}$ . Loss of wood density and  $d_{MOE}$  were greatest in the first months of exposure, and loss of  $d_{MOE}$  was greater than loss of wood density. Lastly, species were grouped by durability: *Alnus acuminata* was the species with the lowest endurance, while species *Terminalia oblonga*, *Gmelina arborea*, and *Vochysia guatemalensis* with low durability were grouped. The species *Bombapcis quinata*, *Terminalia amazonia*, and *Cupressus lusitanica* composed the intermediate durability group. *A.mangium* was the species with the highest wood durability. *Swietenia macrophylla* and *Tectona grandis* also had high wood durability, but lower than *Acacia mangium*.

KEYWORDS: Fungal decay, wood degradation, mechanical strength, tropical species, ultrasonic waves.

INTRODUCTION

The environmental conditions of tropical regions, such as high temperatures and rainfall throughout the year, as occur in Costa Rica, enable the development of a large variety of

forest plantation timber species (Petit and Montagnini 2004). Many of these species have been successfully planted for commercial purposes (Nichols and Vanclay 2012); however, according to Moya and Muñoz (2010), the lack of knowledge about their wood properties or processing, as well as durability, has been an obstacle to their utilization. Studies have been initiated recently on the physical and mechanical properties (Moya and Muñoz 2010), performance during the drying process (Moya et al. 2013), calorific properties (Moya and Tenorio 2013) and degradation of surface finishes of wood from these species (Salas et al. 2015).

However, one of the main uncertainties about wood from fast-growth plantations is about its natural durability (Moya et al. 2009), which is defined as wood's resistance to attacks by biotic and abiotic agents (Mora et al. 2006). Wood durability is related to the end use conditions (Amusan et al. 2014) and is measured when the wood is in direct contact with soil and water, since these are optimum moisture and oxygen conditions for microorganism growth (Márquez 2008). In tropical climates, the conditions of use are more unfavorable, since there are more agents of biodeterioration (e.g. microorganisms and insects) than there are in temperate climates (Mora et al. 2006, Rodrigues et al. 2010).

In addition to conditions of use, there are other conditions intrinsic to the wood that are associated with natural durability, such as the amount of extractive compounds contained in its heartwood and its specific gravity (Ona et al. 1997). It has also been found that some hardwood species can exhibit high natural durability because of low moisture content, lower diffusion rates, presence of extractives in cell cavities and nano-porous walls, and perhaps infiltration of tyloses in vessels (Panshin and de Zeeuw 1980).

Field tests, using wood stakes, are the means to understand the biodegradation process of wood in use (Mattos et al. 2014). In addition, at these test sites it is possible to determine the toxic efficacy of chemical preservatives (Magalhães et al. 2012). Perhaps the most important factors in field tests are site conditions and the duration of testing (Brischke et al. 2009). It has long been recognized that deterioration is more rapid in warm, moist climates than in cool or dry climates, and in tropical regions, 3–5 years of data have generally been considered to be sufficient (Lebow and Clausen 2009).

Currently, the extent of decay in laboratory and field trials is generally determined by loss of weight, visual inspection, and static bending and compression properties. Another approach, using the dynamic modulus of elasticity ( $d_{MOE}$ ) method, was introduced as a possible method for evaluating the extent of decay in wood durability tests (Machek et al. 2004). These researchers found that the decrease in MOE by this method was highly correlated to the degradation of wood by fungi.

Non-destructive methods have recently been developed to identify and determine wood properties without altering final application capacity (Ross et al. 1998). In cases of mechanical resistance, these assessments can be performed with an ultrasound (Oliveira et al. 2002). Applying non-destructive methods in field tests has been used to establish natural durability by different authors (Reinprecht and Hibký 2011).

It is important to understand the behavior of tropical tree species from fast growing plantations regarding natural durability and the effects of treatment with preservatives on durability of wood so as to make better decisions on the possible uses and markets for those species. Therefore, the present study researches the variation in density and the dynamic modulus of elasticity of wood (non-destructive test), both preserved and non-treated, during a 36-month field test of 10 plantation tree species growing in tropical climate conditions (*Acacia mangium*, *Alnus acuminata*, *Bombacopsis quinata*, *Cupressus lusitanica*, *Gmelina arborea*, *Swietenia macrophylla*, *Tectona grandis*, *Terminalia amazonia*, *Terminalia oblonga*, and *Vochysia guatemalensis*).

## MATERIAL AND METHODS

### Selection and preparation of the material

Ten different pure plantations located in several parts of Costa Rica were studied: *Acacia mangium*, *Alnus acuminata*, *Bombacopsis quinata*, *Cupressus lusitanica*, *Gmelina arborea*, *Swietenia macrophylla*, *Tectona grandis*, *Terminalia amazonia*, *Terminalia oblonga*, and *Vochysia guatemalensis*. The initial planting density was 1.111 trees/ha (3x3 m spacing). Some species contained sapwood and heartwood (Tab. 1). At the time of sampling the average age of the trees was 9-18 years old and the density was 495-575 trees/ha (Tab. 1). A total of nine trees per species were randomly selected for harvesting, including suppressed, intermediate, and dominant trees, in accordance with the methodology developed by Moya and Muñoz (2010). Sampled trees, with straight trunks, normal branching, and no disease or pest symptoms, were felled. Two stem sections from the base of the tree to 2.5 m high were obtained from each tree (length of 1.25 m) (Moya et al. 2014b). From these logs, defect-free samples of 45.7 x 8.9 x 3.8 cm were extracted, according to ASTM D-1758-02 (2002) standard method B (ASTM 2014). Four samples for each tree sampled were then randomly selected, and 32 samples extracted from each plantation species. All samples were held in a climate room under controlled conditions (temperature: 20°C; relative humidity: 65 %) to reach the equilibrium moisture content (~12 %).

Tab. 1: Plantation characteristics, heartwood presence, specific gravity, and preservative retention of ten fast-growth tree species in Costa Rica.

Species	Age (years)	Density (trees / ha)	Total height (m)	DBH (cm)	Heartwood (%)	Specific gravity	Retention of preservative (kg.m <sup>-3</sup> )
<i>Alnus acuminata</i>	9	556	20.7	20.5	Absent	0.34	2.7
<i>Acacia mangium</i>	9	338	19.0	36.7	64.45	0.45	2.4
<i>Bombacopsis quinata</i>	10	480	16.7	21.5	Absent	0.32	4.0
<i>Cupressus lusitanica</i>	10	525	20.7	18.5	69.71	0.43	2.1
<i>Gmelina arborea</i>	9	468	25.0	25.1	45.67	0.40	4.1
<i>Swietenia macrophylla</i>	14	452	21.4	22.6	41.28	0.51	4.8
<i>Tectona grandis</i>	8	490	20.6	22.0	56.7	0.57	3.0
<i>Terminalia amazonia</i>	13	475	21.9	25.2	7.18	0.49	4.3
<i>Terminalia oblonga</i>	18	408	19.2	28.0	24.13	0.55	4.3
<i>Vochysia guatemalensis</i>	8	515	22.7	18.5	Absent	0.32	9.7

### Preservative treatment

The vacuum-pressure method was used for the preservative treatment of the wood. Half of the total number of air-conditioned samples per species (18 samples= 9 sampled trees x 2 samples) were treated with the preservative Wolmanit CX-10® (which is formulated with Bis-(N-cyclohexyldiazoniumdioxy)-copper (3.5), copper hydroxide carbonate (16.3), boric acid) (5.0) and-2/a inoethanol (45), fluoride (2.4), boron (4.9 %), and other components. This preservative was used at a concentration of 2.8 % v/v. All samples were placed into a pilot experimental preservation tank under pressure of 690 kPa (approximately 100 psi). The preservation process consisted of 30 minutes under vacuum and 2 hours of pressure, followed by 15 minutes under vacuum. A colorimetric evaluation was performed on cross sections to identify the areas with preservatives. The samples were weighed before and after the preservation process; for pressure

preservation, the absorption capacity was calculated as the absorption of preservatives (liters) by timber volume ( $m^3$ ), while preservative retention of each species (Tab. 1) was determined by the difference in weight and concentration of the preservative solution. Finally, these samples were again conditioned in a climate room to reach the equilibrium moisture content ( $\sim 12\%$ ).

### Installation and characterization of the field tests

The field test of wood stakes was installed on the central campus of the Instituto Tecnológico de Costa Rica (Fig. 1a), found in the province of Cartago (Latitude:  $9^{\circ}50'59''$  N and Longitude:  $83^{\circ}54'37''$  W), at an altitude of 1100 meters. Climatic data are presented in Fig. 1b-c. The soil used was an andisol, a soil derived from volcanic matter, with its origin in volcanic ash, and enriched with nutrients constantly. This soil is well structured, with good drainage and moisture retention and moderate fertility.

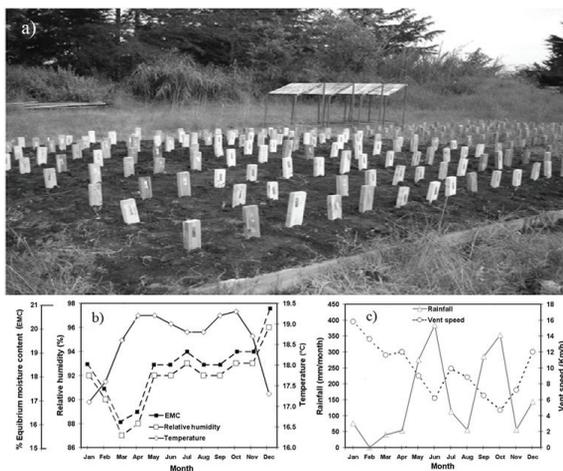


Fig. 1: Field testing a), climatic conditions in the Cartago region, Costa Rica (b and c), location where field tests were installed. Note: meteorological data with at least 3 years of monthly averages from the Instituto Tecnológico de Costa Rica ( $9^{\circ}51'N$ ,  $83^{\circ}54'W$ ) were used to describe the climate.

### Evaluation of samples

The durability of the samples in the field test was quantified every 6 months for a period of 3 years (at 0, 6, 12, 18, 24, 30, and 36 months). The following four parameters were measured in these evaluations: Number of stakes present in each measurement period, the quality of the wood, the density of the samples, and  $d_{MOE}$ . For each evaluation, once measurements had been taken, the samples were removed from the field test and placed in the climate room (temperature of  $20^{\circ}C$ ; relative humidity of 65 %) to reach the equilibrium moisture content ( $\sim 12\%$ ). In determining the number of wood stakes present, during each measurement month, the wood samples that were not broken were counted. The total number of stakes present was considered to determine the degree of permanence, which is expressed as a percent and defined as the number of stakes present in relation to the number of samples at the start of testing. In terms of quality of the samples, each stake was classified according to the specifications of the ASTM standard D 1758-02 (2002) (ASTM 2014), which establishes the following scale: 10- no attack (1 to 2 small perforations made by insects are permitted); 9- perforations on 3 % of the cross section; 8- penetration on 3 to 10 of the cross section; 7- penetration on 10 to 30 of the cross section;

6- penetration on 30 to 50 of the cross section; 4- penetration of 50 to 75 % of the cross section; 0- total failure. For the wood density parameter, conditioned samples were weighed and their dimensions measured; density was determined by their mass and volume, both measured at 12 % moisture content. Lastly, the  $d_{MOE}$  was measured on the longitudinal and transverse dimensions of the stake. This parameter was measured using an ultrasonic wave through the wood. For the longitudinal measurements, the ultrasonic transducer and receptor were placed on either end of the stake and 4 pulses were emitted to determine the average time it took the ultrasonic wave to get from one end to the other. For the transverse measurements, the transducers were placed at the soil line on the stake and again, the average time was measured. Lastly, the velocity of the wave was measured, using the time to cross the section and the distance between the two transducers. The  $d_{MOE}$  was determined using Eq.

$$d_{MOE} = \frac{(V_L)^2 * \rho}{10^6}$$

where:  $V_L$  - velocity of the wave (m.s<sup>-1</sup>),  
 $d_{MOE}$  - dynamic modulus of elasticity (MPa),  
 $\rho$  - density (kg.m<sup>-3</sup>).

### Statistical analysis

A descriptive analysis was performed (average, standard deviation, and maximum and minimum values) for the variables involved: Density and  $d_{MOE}$ . In addition, variable compliance with the assumptions of normal distribution, homogeneity of variances, as well as the presence of outliers, were verified. In terms of percent permanence and quality measured with the ASTM standard 1758-06 (2010) (ASTM 2014), measured percentages were described. As for density and  $d_{MOE}$ , the results are presented in 2 ways: (i) Average densities and  $d_{MOE}$  for each measurement period and their variation over the period of exposure were calculated, and (ii) loss of density or  $d_{MOE}$ , calculated by the difference between the value measured during the measurement period and the value measured 6 months before, were expressed as percentages. Analysis of variance was used to verify the significance of differences among the averages of the variables ( $P < 0.05$ ) for each species, with time of measurement as an independent variable and density and  $d_{MOE}$  as dependent variables. Meanwhile, a Tukey's test was performed to determine the statistical differences overtime of the mean values of each one of the abovementioned variables.

## RESULTS

### Permanence of wood stakes after 3 years of exposure and classification

Percent permanence of the wood stakes, after 36 months of direct contact with ground, varied by species, exposure time, and whether preservatives were used (Tab. 2). In *A. mangium*, *C. lusitana*, *G. arborea*, and *T. grandis*, 100 % of the wood stakes, both preserved and non-treated wood, were present after 36 months. *S. macrophylla* and *T. amazonia* had 100 permanence among preserved wood and 93 permanence in non-treated wood. *B. quinata* had 93 % permanence among preserved wood and non-treated stakes were present at month 36. In *T. oblonga* and *V. guatemalensis*, wood deterioration began at about month 30, but at 36 months, the permanence of preserved wood was 90 and of non-treated wood was 80. Lastly, the species with the lowest percent permanence and that had problems with wood loss was *A. acuminata*. At 18 months, only 80 of preserved and 20 % of non-treated wood stakes remained. Only preserved wood samples remained after month 30 in this species (Tab. 2).

Tab. 2: Percent permanence and quality of preserved (*Wolmanit CX-10*) and non-treated stakes of ten tropical timber species in contact with the ground for 36 months of testing .

Species	Treatment	Month						
		0	6	12	18	24	30	36
<i>Acacia mangium</i>	Treated	100 (10.0)	100 (10.0)	100 (9.1)	100 (8.5)	100 (8.5)	100 (8.4)	100 (8.0)
	Non-treated	100 (10.0)	100 (9.9)	100 (8.8)	100 (8.1)	100 (7.8)	100 (7.5)	100 (7.1)
<i>Alnus acuminata</i>	Treated	100 (10.0)	100 (8.4)	93 (7.2)	80 (6.0)	67 (5.6)	53 (5.4)	53 (5.3)
	Non-treated	100 (10.0)	100 (7.1)	73 (5.0)	20 (4.0)	13 (2.5)	0	0
<i>Bombacopsis quinata</i>	Treated	100 (10.0)	100 (9.9)	100 (9.3)	100 (8.6)	100 (8.6)	100 (8.6)	93 (8.1)
	Non-treated	100 (10.0)	100 (9.5)	100 (8.6)	100 (7.9)	100 (7.3)	93 (7.0)	93 (6.2)
<i>Cupressus lusitanica</i>	Treated	100 (10.0)	100 (10.0)	100 (9.0)	100 (8.9)	100 (8.1)	100 (7.7)	100 (7.3)
	Non-treated	100 (10.0)	100 (9.9)	100 (8.9)	100 (8.5)	100 (7.9)	100 (7.5)	100 (7.1)
<i>Gmelina arborea</i>	Treated	100 (10.0)	100 (9.1)	100 (7.9)	100 (7.4)	100 (7.9)	100 (6.9)	100 (6.5)
	Non-treated	100 (10.0)	100 (8.7)	100 (7.5)	100 (6.9)	100 (6.6)	100 (6.3)	100 (5.5)
<i>Swietenia macrophylla</i>	Treated	100 (10.0)	100 (10.0)	100 (9.7)	100 (9.9)	100 (9.7)	100 (8.9)	100 (8.5)
	Non-treated	100 (10.0)	100 (10.0)	100 (9.7)	100 (8.7)	100 (8.9)	100 (7.5)	93 (7.0)
<i>Tectona grandis</i>	Treated	100 (10.0)	100 (10.0)	100 (8.9)	100 (8.7)	100 (8.5)	100 (8.2)	100 (7.6)
	Non-treated	100 (10.0)	100 (10.0)	100 (8.9)	100 (8.4)	100 (8.1)	100 (7.9)	100 (7.1)
<i>Terminalia amazonia</i>	Treated	100 (10.0)	100 (9.9)	100 (9.1)	100 (8.9)	100 (8.1)	100 (8.1)	100 (7.4)
	Non-treated	100 (10.0)	100 (9.9)	100 (9.1)	100 (8.9)	100 (8.2)	100 (7.8)	93 (7.0)
<i>Terminalia oblonga</i>	Treated	100 (10.0)	100 (10.0)	100 (10.0)	100 (9.6)	100 (9.4)	100 (8.3)	87 (7.9)
	Non-treated	100 (10.0)	100 (10.0)	100 (9.8)	100 (8.5)	100 (8.0)	87 (7.0)	80 (6.3)
<i>Vochysia guatemalensis</i>	Treated	100 (10.0)	100 (9.9)	100 (9.0)	100 (8.3)	100 (7.8)	100 (7.5)	91 (6.4)
	Non-treated	100 (10.0)	100 (9.8)	100 (8.2)	100 (7.9)	100 (6.6)	100 (6.1)	82 (5.6)

<sup>1</sup>Quality of stakes is found in parentheses beside the percent permanence for wood stakes.

## Evaluation of quality

In the quality evaluation, across all tree species tested and at the different exposure times, the preserved samples had higher quality than the non-treated wood, as expected (Tab. 2). *Acacia mangium*, *C. lusitanica*, and *T. grandis*, the species with the highest percent permanence, had wood with quality over 7.1 (Tab. 2). The species *S. macrophylla* and *T. amazonia* were also high quality with values over 7.0 (Tab. 2). *G. arborea*, another species with 100 % permanence, had wood samples of lower quality than the previous group of species. *B. quinata* had quality values over 8.1 in preserved wood, and 6.2 in non-treated wood. *T. oblonga* and *V. guatemalensis* had lower quality values than the above tree species, with 6.4 in preserved and 5.6 in non-treated stakes. Lastly, *A. acuminata* was evaluated as the lowest quality wood, with values of 2.5 at month 24 in non-treated stakes and 5.3 in preserved stakes at month 36 (Tab. 2).

Fig. 2 shows the wood stakes after 36 months of exposure; *A. acuminata* was not present, as no wood samples were found at the end of the exposure test. Another group of species with considerable degradation was *G. arborea*, *T. oblonga*, and *V. guatemalensis*. A group with moderate degradation was made up of *B. quinata*, *C. lusitanica*, *T. amazonia*, and *T. grandis*, while the species with the least wood degradation were *A. mangium* and *S. macrophylla*.



Fig. 2: Appearance of the preserved and non-treated stakes from ten tropical timber species in contact with soil for 36 months of evaluation.

Legend: w/p: non-treated and /p: preserved wood.

### Wood density

In terms of wood density variation and density loss rate at 12 % in moisture content, three groups of species were observed: The first, made up of *A. mangium* and *C. lusitanica*, had density loss rates of less than 4 % in both species in preserved and non-treated wood after 36 months of exposure (Figs. 3a and 3d). In *A. mangium*, density decreased from 0.53 to 0.51 g.cm<sup>-3</sup> in preserved wood and from 0.49 to 0.48 g.cm<sup>-3</sup> in non-treated stakes (Fig. 3a). In *C. lusitanica* (Fig. 3b), wood density decreased from 0.46 to 0.45 g.cm<sup>-3</sup> and from 0.49 to 0.48 g.cm<sup>-3</sup> in preserved and non-treated stakes, respectively.

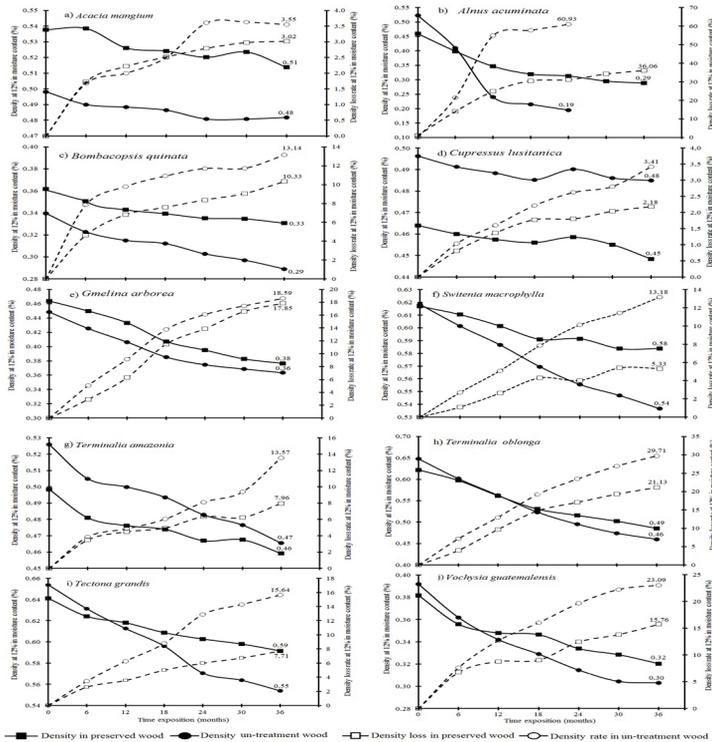


Fig. 3: Variation in wood density and density loss rate at 12 % in stakes exposed to the ground for ten fast-growth plantations in Costa Rica.

The second group of species, made up of *B. quinata*, *S. macrophylla*, *T. amazonia*, and *T. grandis*, each of which experienced density loss rates between 13.18 and 15.64 % in non-treated stakes (Figs. 3c, 3f, 3g, and 3i). Density loss rates were lower in preserved wood, between 5.33 and 10.33 %. Within this group, in non-treated stakes, the species with the greatest density loss was *T. grandis*, with a decrease of 0.65 to 0.55 g.cm<sup>-3</sup> (Fig. 3i), followed by *S. macrophylla* and *T. amazonia*, which decreased from 0.62 to 0.54 g.cm<sup>-3</sup> and from 0.53 to 0.47 g.cm<sup>-3</sup>, respectively (Figs. 3f and 3g). *B. quinata* had the lowest loss of wood density, going from 0.34 to 0.29 g.cm<sup>-3</sup> (Fig. 3c). In preserved wood samples, *B. quinata* had the lowest density loss, going from 0.36 to 0.34 g.cm<sup>-3</sup> (Fig. 3c), followed by *T. amazonia*, which decreased from 0.50 to 0.47 g.cm<sup>-3</sup> (Fig. 3g). The tree species with the greatest loss of density were *S. macrophylla* and *T. grandis*, which decreased from 0.62 to 0.58 g.cm<sup>-3</sup> and from 0.64 to 0.59 g.cm<sup>-3</sup>, respectively (Figs. 3f and 3i).

Within the group of species with moderate loss in wood density (between 18 and 30 %) among the non-treated stakes were *G. arborea*, *V. guatemalensis*, and *T. oblonga*, which experienced decreases in density of 18.59, 23.09, and 29.71 %, respectively (Figs. 3e, 3j, and 3h). Among these, the species with the lowest loss of density was *G. arborea*, which decreased from 0.46 to 0.38 g.cm<sup>-3</sup> (Fig. 3e), followed by *V. guatemalensis*, which decreased from 0.39 to 0.30 g.cm<sup>-3</sup> (Fig. 3j). The greatest loss of wood density in this group was in *T. oblonga*, in which it decreased from 0.65 to 0.46 g.cm<sup>-3</sup> (Fig. 3h). However, in preserved wood, the percent density loss decreased 17.85 in *G. arborea*, 15.76 in *V. guatemalensis*, and 21.13 % in *T. oblonga* (Figs. 3e, 3j, and 3h). The density of preserved wood in *G. arborea* decreased from 0.43 to 0.36 g.cm<sup>-3</sup> (Fig. 3e), followed by a decrease from 0.38 to 0.32 g.cm<sup>-3</sup> in *V. guatemalensis* (Fig. 3j), and a decrease from 0.63 to 0.49 g.cm<sup>-3</sup> in *T. oblonga* (Fig. 3h).

Lastly, the tree species that experienced high density loss throughout the time that it was possible to measure this parameter, both in preserved stakes (36) and in non-treated stakes (60 %), was *A. acuminata* (Fig. 3b). The density of non-treated stakes of this species decreased from 0.50 to 0.19 g.cm<sup>-3</sup> and the density of preserved stakes decreased from 0.45 to 0.29 g.cm<sup>-3</sup>.

One aspect to note is that after one year of exposure, the magnitude of density loss was high in *A. acuminata*, both in preserved and non-treated stakes. While in the rest of the tree species, the greatest magnitude of density loss was reached after 24 months.

### Variation in the dynamic MOE

Between months 6 and 32, the  $d_{MOE}$  in both dimensions used in the study (longitudinal and transverse) was greater in non-treated stakes than preserved wood. The trend in  $d_{MOE}$  over time has an inflection point, the greatest decrease begins from the first month of exposure and continues to a point at which the rate of decrease begins to decline. In *A. acuminata*, *B. quinata*, *C. lusitanica*, *T. amazonia*, *T. oblonga*, *T. grandis*, and *V. guatemalensis* the inflection point occurs within the first 12 months of exposure, while in *A. mangium*, *G. arborea*, and *S. macrophylla*, the inflection occurs at month 18 (Fig. 4).

Another important result is that in *G. arborea*, *S. macrophylla*, *T. oblonga*, and *T. grandis*, it was possible to measure the ultrasonic wave to determine the  $d_{MOE}$  through the total exposure time of 36 months (Fig. 4e, 4f, 4h, and 4i). In the other species it was possible to measure the ultrasonic wave time through month 18 of exposure; no measurements of longitudinal  $d_{MOE}$  were taken after that (Fig. 4a-d, 4g, and 4j).

The percent loss of resistance in the longitudinal  $d_{MOE}$  shows two groups of species (Tab. 3): The first, composed of the tree species in which it was possible to measure the resistance value through month 18 (*A. acuminata*, *A. mangium*, *B. quinata*, *C. lusitanica*, *T. amazonia*, and

*V. guatemalensis*). In this group, *B. quinata* and *T. amazonia*, with losses of 25-42 and 31-54 % were those with the lowest loss of longitudinal  $d_{MOE}$  in both preserved and non-treated stakes. The species *A. acuminata* (72-100) and *V. guatemalensis* (64-82 %) experienced the greatest loss of resistance, while *C. lusitânica* and *A. mangium* experiences an intermediate loss of resistance in comparison to the other tree species.

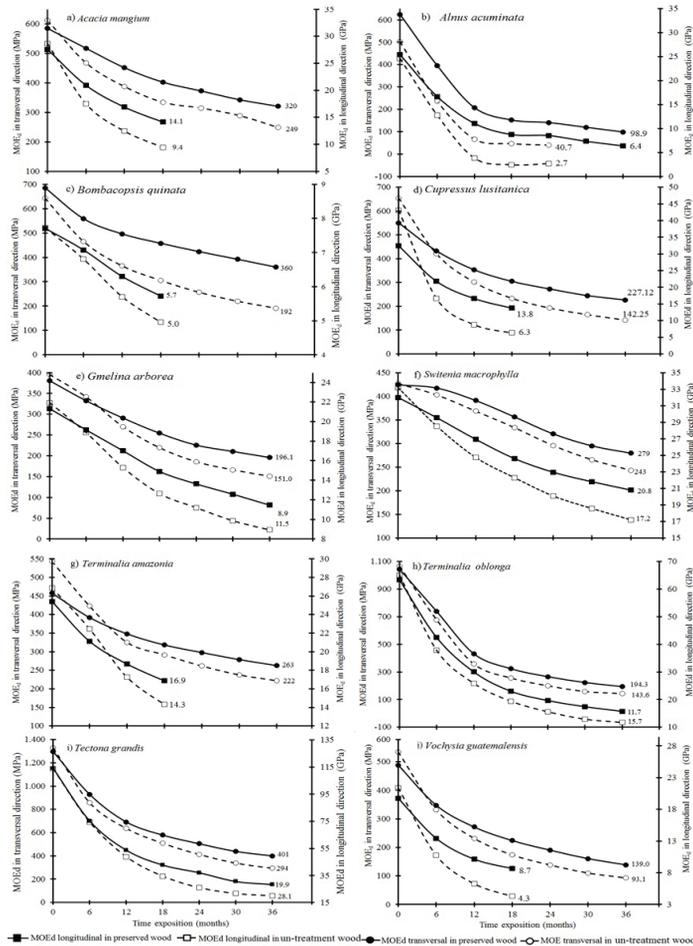


Fig. 4: Variation in the dynamic modulus of elasticity in relation to length of exposure to the ground in ten fast-growth plantation species in Costa Rica.

In the second group, composed of the species in which the longitudinal  $d_{MOE}$  was measured during all 36 months of the study, *S. macrophylla* (38-42) and *G. arborea* (43-64) were the species that experienced the lowest loss of resistance, both in preserved and non-treated stakes. The species *T. grandis* (70-85) and *T. oblonga* (72-80 %) showed the greatest loss in resistance (Tab. 3).

Tab. 3: Percent loss in dynamic modulus of elasticity after 36 months in the ground.

Plantation species	Resistance loss in $d_{MOE}$ in longitudinal direction (%)		Resistance loss in $d_{MOE}$ in transverse direction (%)	
	Preserved stakes	non-treated stakes	Preserved stakes	non-treated stake
<i>Alnus acuminata</i>	72.9	100.0	81.8	100.0
<i>Acacia mangium</i>	46.6	63.4	44.6	58.3
<i>Bombacopsis quinata</i>	25.5	42.2	48.7	70.3
<i>Cupressus lusitanica</i>	56.2	84.6	57.1	77.3
<i>Gmelina arborea</i>	42.9	63.5	47.4	65.5
<i>Swietenia macrophylla</i>	38.1	41.7	44.8	42.0
<i>Tectona grandis</i>	70.2	85.5	79.9	62.4
<i>Terminalia amazonia</i>	31.6	53.6	41.8	56.6
<i>Terminalia oblonga</i>	72.2	80.0	82.5	87.3
<i>Vochysia guatemalensis</i>	63.7	81.7	69.9	81.7

In terms of transverse  $d_{MOE}$ , the species with the lowest loss of resistance were *T. amazonia*, *A. mangium*, *S. macrophylla*, *G. arborea*, and *B. quinata*, with an average of 46 in preserved wood and 58 % in non-treated stakes (Tab. 3). After the previous group, *C. lusitanica* experienced a loss in resistance of 57 in preserved wood and 77 in non-treated stakes (Tab. 3). A third group of species, with the greatest decrease in transverse  $d_{MOE}$ , included *V. guatemalensis*, *T. grandis*, *A. acuminata*, and *T. oblonga*, with an average loss of 79 in preserved wood and 83 % in non-treated stakes.

**Effects of preservative retention on the durability**

Evaluation of the effects of preservative retention on the loss of density in wood found that increased retention does not reduce loss of wood density and  $d_{MOE}$  in all species. In *A. acuminata*, *A. mangium*, *B. quinata*, *G. arborea*, *S. macrophylla*, *T. oblonga*, and *V. guatemalensis* (Fig. 5) increased preservative absorption was found to be negatively correlated with the loss of wood density and of  $d_{MOE}$ . In 3 tree species (*C. lusitanica*, *T. grandis*, and *T. amazonia*), absorption of preservative was not shown statistically to affect wood density loss or decreases in  $d_{MOE}$ .

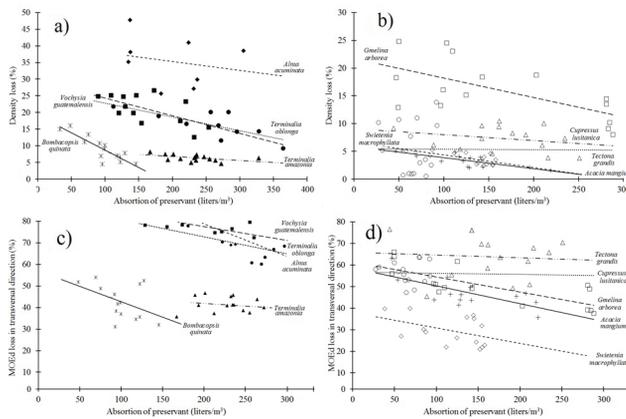


Fig. 5: Relationship between density loss and transverse  $d_{MOE}$  loss with absorption of preservative in 10 fast-growth plantation tree species in Costa Rica.

## DISCUSSION

### Permanence, quality, wood density and dynamic MOE

Evaluations of wood permanence (Tab. 2), quality (Tab. 2), changes in and loss of density (Fig. 3b), and resistance to  $d_{MOE}$  (Fig. 4b) demonstrated that *A. acuminata* is the fast-growth plantation species grown in Costa Rica with the lowest resistance to exposure to the ground, both in preserved and non-treated stakes. For this species, it was observed that declines in stake permanence, loss of density, and decline of resistance began to occur after 18 months of exposure; therefore, this wood is not recommended for use in contact with the ground. The natural durability of wood is related to the presence of heartwood, which has more extractive compounds compared to sapwood, resulting in greater natural durability (Windeisen et al. 2002, Kirker et al. 2013). The relationship of durability with extractive compounds is mainly due to phenolic compounds (Bultman and Southwell 1976, Syofuna et al. 2012). The plantation species *A. acuminata* was observed to lack heartwood (Moya and Muñoz 2010) and has low levels of extractive compounds, found with extraction in an ethanol-toluene solution (Moya and Tenorio 2013), which is an indicator of phenolic extractive compounds (Moya et al. 2012).

The low resistance of preserved wood from *A. acuminata* can also be explained by the low preservative retention (Tab. 1) and by the irregular penetration of the preservative in the wood, which is classified as partial irregular-vascular (Moya et al. 2014b). In this type of preservation, complete protection of the wood is not achieved, as there are regions left unpreserved, which are susceptible to attacks by microorganisms (Cowie et al. 1989).

A second group of low durability, but higher than that of *A. acuminata*, was composed of *T. oblonga* and *V. guatemalensis*. In these species, the permanence of the wood stakes was low, as was the index of wood quality (Tab. 2). This low durability was supported by high losses of wood density and high reduction in resistance over the length of exposure (Fig. 3, Tab. 3).

A third group in terms of durability, formed by *S. macrophylla* and *B. quinata*, had intermediate levels among the parameters evaluated. *G. arborea* and *T. amazonia* can be grouped with the above species (intermediate durability), but the values for loss of  $d_{MOE}$  in these species are not consistent with them, because *G. arborea* and *T. amazonia* are classified as high durability, since there was little decline in the rate of  $d_{MOE}$  loss. In *T. grandis*, although this species had high stake permanence (Tab. 2), the values for loss of mechanical resistance ( $d_{MOE}$ ) classify it as low durability, with higher wood degradation than other plantation species. This result may contradict some references (Moya et al. 2014b), since they classify it as high durability (Schefer 1966). This may be explained by the fact that in this study, wood from 8 year old trees was used, which have not yet produced tectoquinone, the extractive compound that gives teak its high natural durability (Moya et al. 2014a). In another study with wood of this age and origin, the heartwood was found to have low durability (Moya et al. 2009, Haupt et al. 2003).

Two important aspects to emphasize from the results on loss of density and  $d_{MOE}$ , independently of preservation, are that mechanical resistance decreased in the first months of exposure and that the loss of resistance was greater than the decrease in density (Figs. 1 and 2). The loss of density and  $d_{MOE}$  during the first months is related to exposure in tropical climates, where biodegradation occurs mainly by brown rot fungi (Bultman and Southwell 1976). During the initial stages of brown rot, the fungi initiate colonization and releases enzymes, but damage to the wood is not observed. However, during this time, chemical changes to cell walls, specifically polysaccharide components (cellulose and hemicellulose), occur in the S2 layer, but not in the lignin (Curling et al. 2002), resulting in a reduction in the mechanical resistance of wood (Clausen and Kartal 2003) in the first months of exposure. In estimates made for species

exposed to temperate climates, loss of resistance can reach 10 % (Wilcox 1978), which is lower than the values found in the plantation species studied (Tab. 3). Nevertheless, this value must be compared carefully, since the wood studied was evaluated in a tropical climate, where the conditions for degradation are more severe (Onyekweli 2003) and since the wood used was derived from plantations, where durability is generally lower than in wood from natural forests (Moya et al. 2009).

The relationship between greater decreases in  $d_{MOE}$  and loss of weight or density, as evaluated in this study, can be explained by the degradation of polysaccharides in initial stages of decay and by the degradation of lignin in the later stages (Venäläinen et al. 2014). For example, in laboratory tests, it has been found that loss in strength may exceed 50 by the time 10 % weight loss has been incurred (Clausen and Kartal 2003).

### Effects of preservation on wood

Preservation increased the permanence and quality of the wood stakes and decreased the losses of density and  $d_{MOE}$ , as expected. These results are consistent with those found for other tropical tree species from plantations in field tests (Mattos et al. 2014, Magalhães et al. 2012). However, loss of density and resistance of preserved wood was found to be related to the presence or absence of heartwood, the type of penetration of the preservative (regular, irregular, or vascular), and to the absorption of the preservative. For example, in *A. mangium*, *B. quinata*, and *G. arborea* it is not possible to preserve the heartwood (Moya et al. 2014b).

This likely resulted in little difference in wood density loss between the preserved and non-treated stakes (Fig. 3), and in fact, the appearance of the wood samples is similar at month 36 of exposure (Fig. 2). Since the absorption of preservative was low (Tab. 1), the protection provided when in contact with the ground was also low. *Acacia mangium* and *B. quinata* also had the issue of unpreserved heartwood and irregular preservative penetration in the sapwood (Moya et al. 2014b), which does not ensure good protection from the preservative for wood in direct contact with the ground. *Cupressus lusitanica*, *T. amazonia*, *T. oblonga*, and *T. grandis* had intermediate values for loss of density and  $d_{MOE}$ . In this third group, the quantity of preservative absorbed was moderate in relation to other species, which had higher preservative absorption (Tab. 1).

These 4 species have some level of heartwood development (24.13 to 56.7 %), with the exception of *T. amazonia*, where heartwood development and regular preservative penetration make the preservative treatment effective in the species. In *T. amazonia*, good protection against biodegradation is achieved because most of the wood is sapwood and irregular preservative penetration is achieved (Moya et al. 2014b). Lastly, the large difference between preserved and non-treated wood found in *A. acuminata*, *S. macrophylla*, and *V. guatemalensis* can be explained in each species. In *V. guatemalensis*, good protection is achieved because of high absorption (Tab. 1) and regular penetration of the preservative (Moya et al. 2014b). In *A. acuminata*, the same levels of protection were not achieved, since retention was low and the permanence of its wood was less than the 36 months of exposure. Likewise, the difference between preserved and non-treated stakes in *S. macrophylla* is due to regular preservative penetration in the sapwood, which gives it adequate protection.

Likewise, an important aspect to highlight is an increase in the volume of preservative absorbed significantly decreases density loss in *A. acuminata*, *A. mangium*, *B. quinata*, *G. arborea*, *S. macrophylla*, *T. oblonga*, and *V. guatemalensis* (Fig. 5), which makes the absorption of preservative a factor that can be controlled in these species to diminish the negative effects of exposure to the ground on density and  $d_{MOE}$ . Where as in 3 species (*C. lusitanica*, *T. grandis*, and *T. amazonia*), the quantity of preservative used did not affect the decrease in these parameters (Fig. 5).

This variation between groups of species is associated with the presence of heartwood. In the first group, low percentages of heartwood (0.0 to 45.7 %) were found, while the second group of species is characterized by high percentages of heartwood, 56.0 to 69.7 % (Tab. 1). These results suggest that in the first group of species, the wood durability can be controlled with increased absorption due to high sapwood proportions, while in the species with high percentages of heartwood, the durability cannot be controlled by preservative absorption because it is limited in this type of wood.

## CONCLUSIONS

The evaluations of wood permanence, quality, change and loss of density, and  $d_{MOE}$  resistance demonstrated that *A. acuminata* was the fast-growth plantation tree species in Costa Rica with the lowest resistance to exposure to the ground, both in preserved and non-treated stakes, with resistance of about one year. A second group of lower durability was made up of *T. oblonga*, *G. arborea*, and *V. guatemalensis*. Another group with similar durability among the species and lower than the previous group was composed of *B. quinata*, *T. amazonia*, and *C. lusitanica*. The species with highest durability was *A. mangium*. The species *S. macrophylla* and *T. grandis* also had high durability, but lower than that of *A. mangium*.

The magnitude of decreases in density and  $d_{MOE}$ , independently of preservation, was greater in the first months of exposure in all species; likewise, it was determined that the magnitude of the loss of resistance was greater than that of the decrease in density.

In *A. acuminata*, *A. mangium*, *B. quinata*, *G. arborea*, *S. macrophylla*, *T. oblonga*, and *V. guatemalensis*, an increase in the absorption of preservative was found to be negatively correlated with wood density loss, while in *C. lusitanica*, *T. grandis*, and *T. amazonia*, absorption of preservative was not shown statistically to affect loss of wood density or  $d_{MOE}$ .

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RÓGER MOYA\*, ALEXANDER BERROCAL  
INSTITUTO TECNOLÓGICO DE COSTA RICA  
ESCUELA DE INGENIERÍA FORESTAL  
P.O. BOX: 159  
7050 CARTAGO  
COSTA RICA  
PHONE: (506) 2550-2433  
\*Corresponding author: rmoya@itcr.ac.cr