

APPLICATION OF X-RAY TECHNIQUE IN NONDESTRUCTIVE EVALUATION OF EUCALYPT WOOD

M. Tomazello¹, S. Brazolin², M. P. Chagas¹, J. T. S. Oliveira³, A. W. Ballarin⁴,
C. A. Benjamin⁴

¹Departamento de Ciências Florestais/USP, Piracicaba. SP; ²Instituto de Pesquisas Tecnológicas do Estado de São Paulo, SP; ³Departamento de Ciências Florestais/UFES, Alegre. ES; ⁴Faculdade de Ciências Agrônomicas/UNESP, Botucatu. SP; Brasil

Corresponding author: mtomazel@esalq.usp.br

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ABSTRACT

X-rays were initially used for the inspection of special-purpose wood pieces for quantitative evaluation of wood properties of different species. X-ray densitometry has had its use expanded in dendroclimatology of *Picea engelmannii* trees. Subsequent laboratories developed applications of X-ray densitometry for environmental, wood science and technology, and related areas. This paper describes the basic methodology of X-ray densitometry applied to the eucalypt wood analysis, as well as presenting the results of applications in three areas: (i) evaluation of wood biodegradation by white rot fungi, (ii) detection of sapwood and heartwood, and (iii) determination of the effect of management on wood properties. The wood decayed by white rot fungi was detected by X-ray densitometry with a decreasing wood density due to the biodegradation of cell wall components. The sapwood and heartwood of eucalypts were separated in response to the attenuation of X-rays, reflected by the wood anatomical structure and chemical composition. Also, in eucalypt trees after the application of irrigation and fertilization-irrigation characteristic wood density profiles were detected. In addition, the significant potential of X-ray densitometry for eucalypt wood research and analysis is discussed.

Keywords: Eucalypts, X-ray densitometry, sapwood, heartwood, density, white rot fungi.

1. INTRODUCTION

The earliest literature indicates that the use of the X-rays in the inspection of wood pieces began in the last century (Worschitz 1932, Fischer and Tasker 1940) through the qualitative wood evaluation for specific applications, such as tree poles, propellers, and other parts of airplanes in the examination for internal defects (knots, internal cracks, biological decomposition, wood boring insects, etc.). Later, several authors (Legrand 1946, Lenz, 1957, Jacquot 1961, Polge 1963) applied X-ray densitometry for the quantitative evaluation of wood properties of different forest species and wood products. The use of X-ray densitometry was expanded by Parker (1971) when correlating climatic variables with density parameters of annual tree-rings of *Picea engelmannii*. Subsequently, researchers in different laboratories expanded the applications of X-rays (Sardinha, 1974, Schweingruber *et al.* 1978, Amaral and Tomazello Fo 1994, among others). Despite extensive literature on the application of the X-ray densitometry for wood analysis the information on eucalypts is very limited. The results of the wood analyses of different eucalypt species have been published largely by few authors in Brazil, Portugal, and Australia (Nicholls and Griffin 1978, Nicholls and Matheson 1980, Jorge 1994, Bucur *et al.* 1994, Lausberg *et al.* 1995, Evans and Downes 1995, Tomazello *et al.* 1995, Oliveira 1997, Silva 2002, Wimmer *et al.* 2002, Silva *et al.* 2004, Alzate 2004, Moya *et al.* 2005, Benjamin 2006, Tomazello 2006).

2. The methodology of wood X-ray densitometry in *Eucalyptus spp*

Preparation of wood samples. The wood samples for densitometric analyses can be obtained destructively (harvesting the trees and cutting wood cross-sections) or nondestructively (mechanical extraction with an increment borer). In wood cross-sections, diametrical samples were demarcated and cut (20 x 10 mm, width x height) and placed in a supporting fixture; in the same procedure, wood cores from nondestructive samples were similarly supported, with the fibers in the horizontal direction. The samples were cut in the transverse orientation (2.0 mm thickness) with double circular saws. The thin wood samples were stored in a conditioning chamber (12 h, 20°C, 50% RH) until reaching 12% moisture content (**Figure 1**).

Obtaining the wood radiographic films. The wood samples and a calibration wedge of cellulose acetate (density: 1.48 g/cm³) were placed on an X-ray film (Kodak, Diagnostic Film T-Mat, 240 x 180 mm) in darkroom conditions. They were then transferred to the X-ray equipment (Hewlett Packard, Faxitron 43805 N; 1.20 m distance from source to X-ray-film) and X-rayed (5 min exposure, 16 kV accelerating voltage, 3 mA heating current of the cathode). The radiographic film was read with a Macrotec MX-2 (Amaral and Tomazello 1998).

Analysis of the wood radiographic films. The radiographic films were digitalized with a scanner (Hewlett Packard ScanJet 6100C/T) to a resolution of 1000 dpi (pixels/in.) with a gray scale of 256 degrees. In the digitalized image, comparisons were made of the gray scale of the wood samples and the calibration wedge, and the density values were converted into a file (DEN), using CRAD software. In this sequence, the file DEN was read with aid of the software CERD considering 500 x 10 µm (length x width) density measurements for segments of 25% of the length of the wood samples.

Wood density radial profile. The analyses of the wood samples generated a file containing the values of wood density and the respective corresponding wood density profiles of the eucalypt trees (Mothe et al. 1998). Using the wood density profile it is possible to calculate other parameters, such as mean, maximum, and minimum densities.

3. The X-ray technique in nondestructive evaluation of eucalypt wood

3.1. Wood decay detection of eucalypts through X-ray densitometry

Despite the common usage of wood in construction and structures, it has the disadvantage of biodegradation by fungi. The mycelium of the fungi can decompose the wood internally, forming discreet stains or spots of different sizes that are difficult to detect by external examination. For this condition, nondestructive methods have been recommended for the analysis of the interior of the wood using radiographic images. More recently, with the development of equipment and methods of analysis of digital images of radiographic films, it has been possible to determine the variations of the apparent density values of affected and healthy wood (Amaral and Tomazello 1998).

Species and wood sample collections. For X-ray densitometry analysis, 4 diametrical wood samples were collected at the DBH of 8-year-old *Eucalyptus grandis x urophylla* having normal wood and areas infected by white rot fungi. Also, wood microslides of the healthy and affected areas were cut with a sliding microtome, stained with safranin and picroanilin, and observed under a microscope (Tomazello 1998).

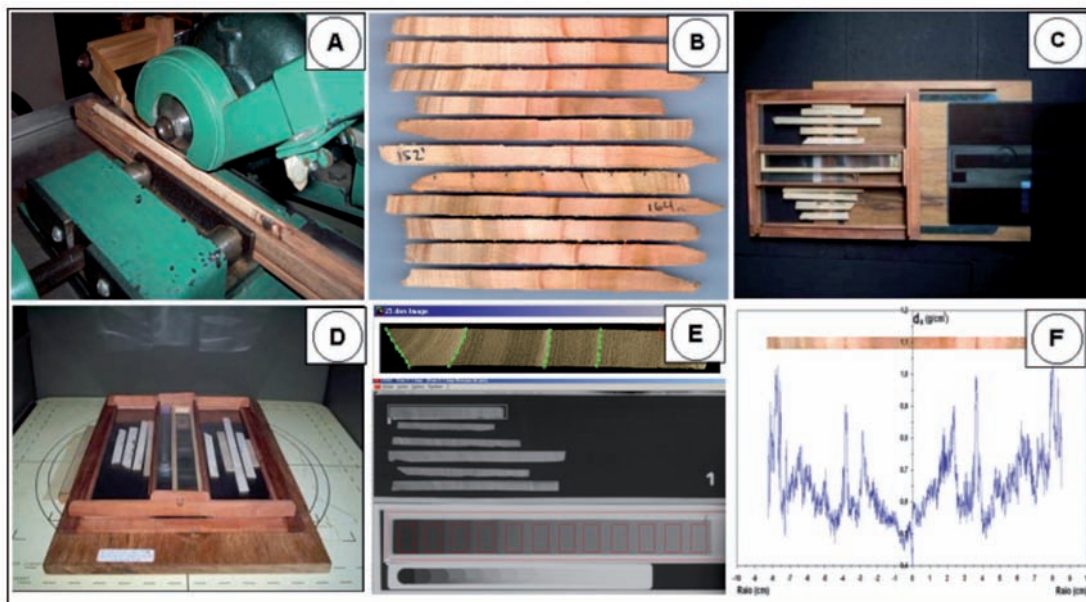


Figure 1: X-ray methodology and eucalypt wood radiographs: (a) wood samples are supported and cross-sections are cut with double parallel circular saws; (b) wood cross-sections; (c) wood samples and cellulose acetate wedge on radiographic film; (d) irradiation of the wood samples in X-ray equipment; (e) wood radiographic image and analysis in CRAD and CERD programs; (f) double-radial (bark-bark) wood density profile and respective wood cross-section.

Results. In the cross-sections of sapwood there were limited areas of whitish color and porous appearance that formed discreet stains or spots, characteristic of white rot fungi decomposition. The effect of the action of these fungi can be clearly observed in the wood density profiles of the eucalypt wood sample No. 92 (**Figure 2**). In the total eucalypt wood samples analyzed the mean wood density of the healthy vs. the affected areas was reduced from 0.71 to 0.59 g/cm³; the maximum and minimum wood densities varied from 0.95 to 0.83 and 0.57 to 0.44 g/cm³, respectively. The reduction of wood density (17-23 %) resulted from the white rot fungi decomposition of the wood cell wall constituents, lignin, cellulose, and hemicelluloses. Applying the similar methodology, Bucur *et al.* (1997) observed a reduction in wood density of 25% in the *Fagus sylvatica* with white rot (*Trametes versicolor*) and of 18% in *Pinus sylvestris* with brown rot (*Gloeophyllum trabeum*) after long time of exposure (5 months of incubation) under laboratory conditions. The wood becomes more permeable and hygroscopic due to the anatomical-chemistry alterations of the cell wall components and the destruction of the pit membranes, resulting in drastically affected mechanical properties of wood (Wilcox 1973, Oliveira 1986, Eaton and Hale 1993). In the advanced phases of fungal attack, the presence of holes and a reduction of the thickness of secondary cell wall (beginning at the interface of the S3 layer) are observed. The vessels of some hardwood species are slightly affected; the cell wall corners and middle lamella have greater resistance to the biodegradation and are degraded only in the final stages of the wood decomposition (**Figure 3**).

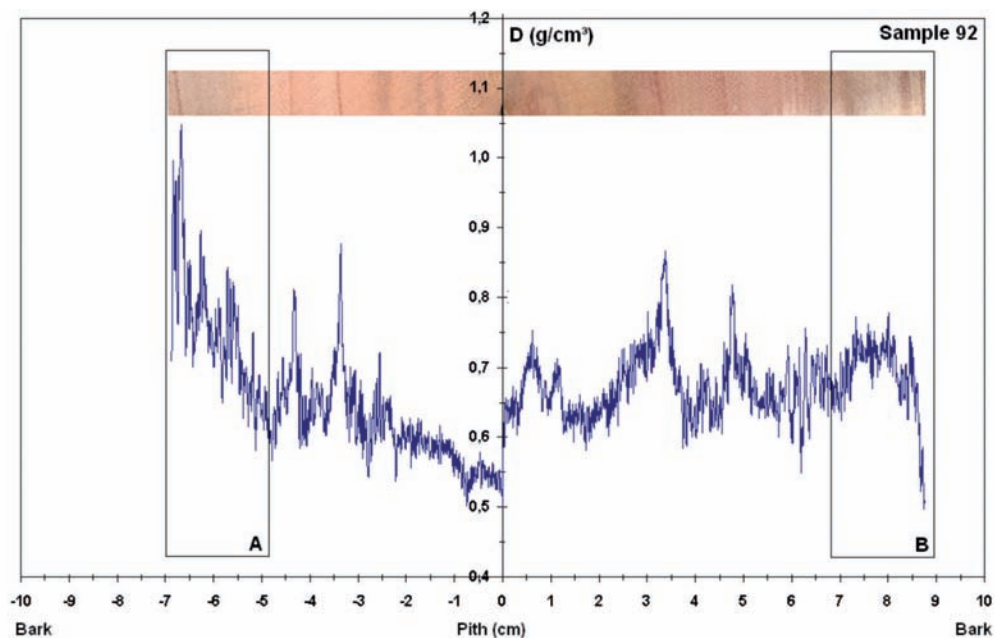


Figure 2: Wood density profile (sample 92) of *Eucalyptus grandis x urophylla*.
A -healthy and B - affected area of white rot fungi.

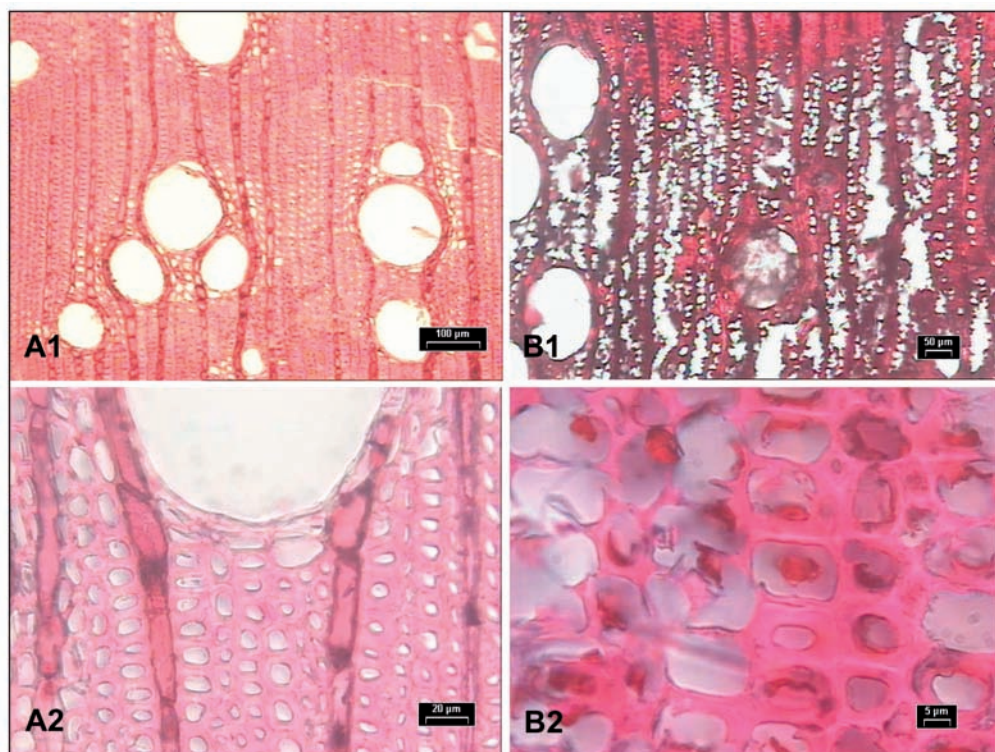


Figure 3: Wood microscopic features of *Eucalyptus grandis x urophylla*.
A1,2- healthy; and B1,2 - affected area of white rot fungi.

3.2. Sapwood-heartwood of *Corymbia citriodora* by the X-ray densitometry

The visual separation of heartwood and sapwood for some species is very difficult due to little contrast in color. The presence and amount of heartwood-sapwood in eucalypt trees alters the wood technological properties and applications, like solid wood, pulp and paper, panels, particleboard, etc. (Bamber and Fukazawa 1985). In these species the application of X-ray densitometry can be extremely useful to identify the sapwood-heartwood boundaries, based on different wood properties and levels of X-ray attenuation.

Species and wood sample collections. For X-ray densitometry analysis, 6 wood samples were collected at the DBH of 29-year-old *Corymbia citriodora*. Wood samples (10 x 10 x 10 mm) were obtained from sapwood and heartwood, and the cross-sections were polished using a sliding microtome for microscopic examination of the tyloses (Tomazello 1998).

Results. In the wood cross-sections, sapwood and heartwood were examined in the X-ray wood density profile of the sample No. 6 (**Figure 4**). The mean wood density of the heartwood is significant greater (ANOVA, 5% level) than the sapwood, 1.31 vs. 1.14 g/cm³. Likewise the maximum and minimum wood densities were 1.48 vs. 1.34 and 1.11 vs. 0.91 g/cm³, respectively, with significant differences (ANOVA, 5% level to minimum wood density) (**Table 1**). The wood density increase results from the tyloses development in the lumen of vessels, as well as the deposition of heartwood substances (tannins, oils, etc.) in the radial parenchyma cells. The heartwood becomes darker, with lower permeability and higher natural resistance against microorganisms. There is greater attenuation of X-rays in the heartwood from the xylem cells containing tyloses and chemical components; whereas the sapwood lower density is a result of functional xylem with open vessels.

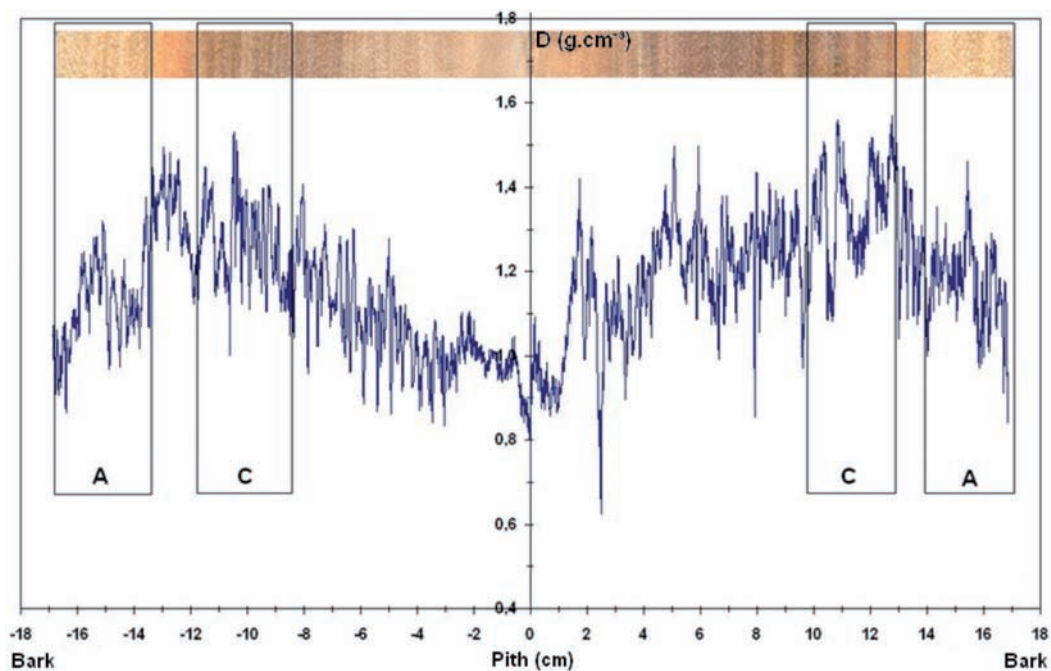


Figure 4: Wood density profile of sample No. 6 of *Corymbia citriodora*.
A - sapwood and C - heartwood areas.

Table 1: Wood density of sapwood (A) and of heartwood (B) of *Corymbia citriodora*.

Sample	Radio	Wood density (g.cm ⁻³)					
		D _{average}		D _{maximum}		D _{minimum}	
		H	S	H	S	H	S
1	R	1.18	1.07	1.32	1.19	1.07	0.94
	L	1.37	1.21	1.54	1.43	1.19	1.01
2	R	1.38	1.16	1.55	1.41	1.23	0.89
	L	1.25	1.11	1.35	1.24	1.15	0.91
3	R	1.36	1.18	1.57	1.46	1.04	0.84
	L	1.29	1.11	1.53	1.32	1.00	0.87
Stand. Dev.		0.08	0.05	0.11	0.11	0.09	0.06
Mean		1.31 a	1.14 b	1.48 a	1.34 a	1.11 a	0.91 b

R (right) and L (left) radius orientation; H (heartwood) and S (sapwood) of wood samples. Mean values followed by the same letter are not significantly different at the 5% level

3.3. Eucalypt management and evaluation of wood quality by X-ray densitometry

The Brazilian eucalypt forest plantations have been treated experimentally to induce higher wood productivity. The results of experimental areas indicate a volume of 34 m³/ha/yr (without fertilization) to 49 m³/ha/yr (with fertilization) and as high as 51 m³/ha/yr (extreme fertilization); irrigated plantations have produced from 63 m³/ha/yr to 68 m³/ha/yr, when fertilization has been added. However, it is important to evaluate the wood properties even though the main objective is to increase the wood volume (Raymond and Muneri 1998, Beadle *et al.* 2001) through appropriate techniques such as X-ray densitometry (Tomazello 2006).

Species and wood sample collections. For X-ray densitometry analysis, 30 diametrical wood samples were collected at the DBH of 7.11-year-old *Eucalyptus grandis x urophylla*, exposed to the treatments: control (CN), irrigation (CI), and fertilization/irrigation (FI), following a period of 3.1 years of common forest management applied to all trees.

Results. The wood density profiles of the samples of eucalyptus trees having the three treatments (CN, CI, FI) are presented in **Figure 5** and **Table 2**. Initially, the total radial length of the samples was 6.5, 8.5-9.5, and 9.0 cm for CN, CI, and FI, respectively, showing significant differences (ANOVA 5% level) of the irrigated and fertilized/irrigated to the control. The increase of the external diameter of the eucalypt trunks exposed to fertilization/irrigation has been shown for a few eucalyptus species and sites (Beadle *et al.* 1997, 2001, Raymond 1998), as a result of stimulating the cambium from supplementary addition of water and nutrients in the soil. However, the wood density profile makes it possible to verify and quantify important and significant responses of the trees to each treatment: the second tree-ring from the pith (indicated by the arrows) delimited an internal wood core formed before the application of the treatments and common to all the eucalypt trees. The internal wood core of the eucalypt stems, with 4.0-4.5 cm radius, formed before the application of the treatments, presented the mean wood density of 0.61, 0.63, and 0.60 g/cm³ to the treatments CN, CI, and FI, respectively, with no significant differences

(ANOVA 5% level). The external core of the eucalypt stems formed after the application of the treatments presented 2.8, 4.0, and 4.3 cm lengths in CN, CI, and FI, respectively. The external core of eucalypt stems has characteristic variations of wood density, in addition to the differentiated radial length. For the CN treatment, the wood density has significant variability, higher values of wood density (significant difference, ANOVA 5% level), and formation of several growth layers; in CI and FI, the wood density has smaller value and variability and with 2-3 growth layers. Analyzing the wood density profile of *E. grandis x urophylla* verified similarities with the literature: smaller values of wood density in the stem central region, with progressive increases in direction to the bark; oscillations of the density values in the pith-bark direction due to (i) vessels of larger diameter and (ii) layers of thickened cell wall fibers and smaller vessel diameters, with similarities for the same hybrid (Alzate 2004).

Table 2: Wood density of *Eucalyptus grandis x urophylla* trees in relation to the period of the treatments application.

Treatment	Wood density (g.cm ⁻³)		
	Mean	Minimum	Maximum
Total treatments			
1CN	0.66 a (0.01)	0.48 a (0.02)	1.07 a (0.05)
2CI	0.66 a (0.02)	0.52 b (0.02)	1.06 a (0.05)
3FI	0.63 b (0.03)	0.46 a (0.04)	0.97 b (0.08)
Before Treatments			
1CN	0.61 a (0.02)	0.49 a (0.02)	1.02 a (0.08)
2CI	0.63 a (0.02)	0.52 b (0.02)	1.02 a (0.08)
3FI	0.60 a (0.05)	0.47 a (0.04)	0.93 b (0.09)
After treatments			
1CN	0.72 a (0.03)	0.55 a (0.03)	1.06 a (0.06)
2CI	0.69 ab (0.03)	0.54 a (0.04)	0.99 ab (0.07)
3FI	0.65 b (0.05)	0.49 b (0.05)	0.93 b (0.10)

CN: control; CI: irrigated; FI: fertilized and irrigated eucalypt trees. Mean values followed by the same letter are not significantly different at the 5% level

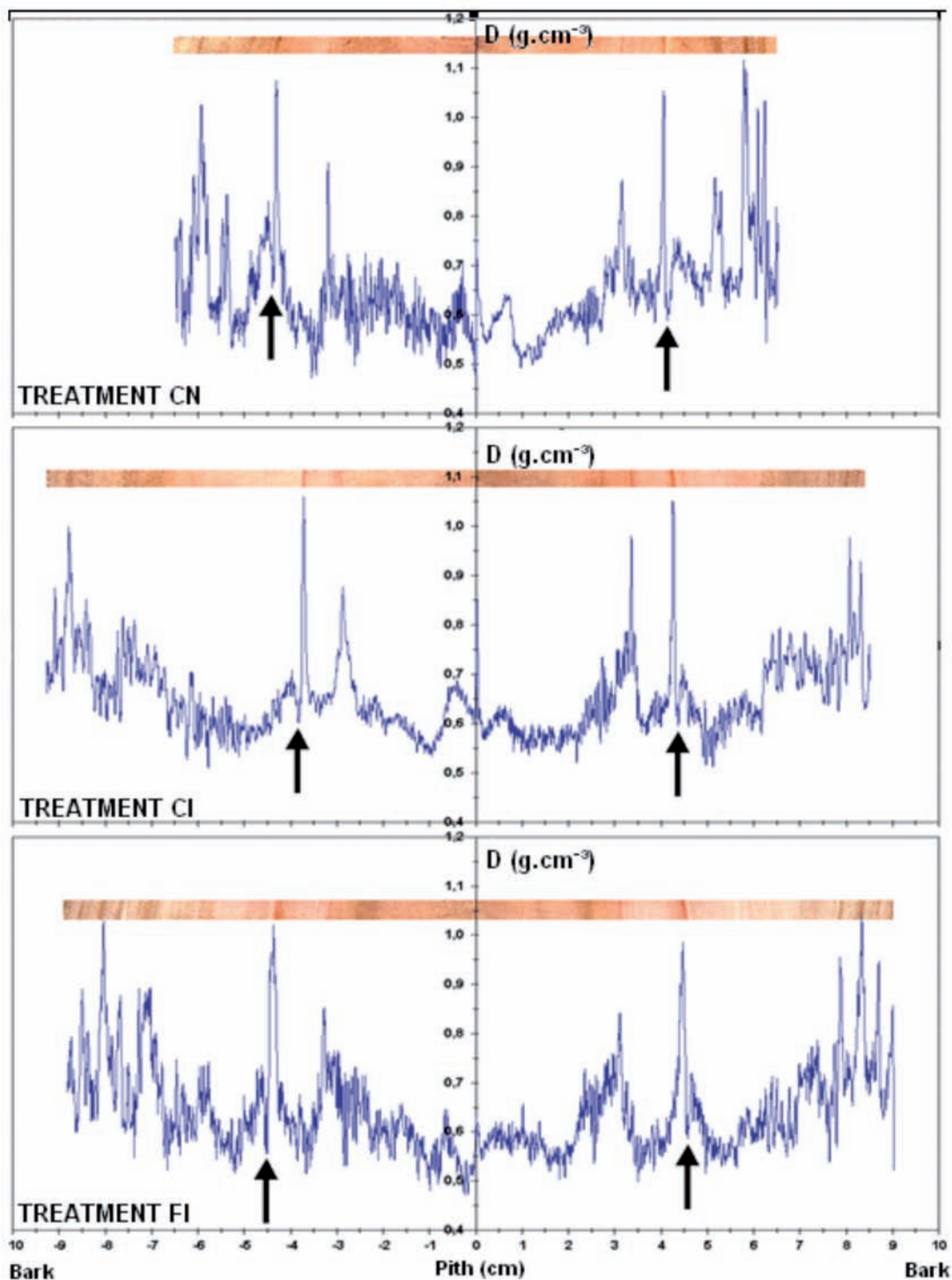


Figure 5: Wood density profiles of samples No. 22, 17, and 12 of *Eucalyptus grandis x urophylla*, having treatments CN, CI, and FI, respectively. Arrows indicate the beginning the treatments in all the trees with 3.1 years; trees were harvested at 7.11 years.

4. CONCLUSIONS

The decay of eucalypt wood by white rot fungi can be detected by X-ray densitometry as shown by a decrease in the mean, minimum, and maximum wood density. The reduction of wood density is from the biodegradation of cell wall components by the mycelium of white rot fungi.

The X-ray densitometry permits differentiation of sapwood and heartwood of eucalypts due to differences in anatomical structure and chemical composition. These differences in sapwood and heartwood are reflected in the attenuation of X-rays because of the variations in wood density.

X-ray densitometry of the wood density profile made it possible to detect the response of eucalypts exposed to different management treatments: control, irrigation, and fertilization/irrigation.

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