Floram
Floresta e Ambiente

Floresta e Ambiente 2018; 25(2): e20170659
http://dx.doi.org/10.1590/2179-8087.065917
ISSN 2179-8087 (online)

Original Article

Wood Science and Technology

Water Flow Evaluation in *Eucalyptus* and *Corymbia* Short Logs

Thiago Monteiro[1], José Lima[2], José Silva[2], Antonio José Zanuncio[3], Edy Baraúna[4]

[1]Departamento de Engenharia e Tecnologia Florestal, Universidade Federal do Paraná – UFPR, Curitiba/PR, Brasil
[2]Departamento de Ciências Florestais, Universidade Federal de Lavras – UFLA, Lavras/MG, Brasil
[3]Instituto de Ciências Agrárias, Universidade Federal de Uberlândia – UFU, Campus Monte Carmelo, Monte Carmelo/MG, Brasil
[4]Instituto de Ciências Agrárias, Universidade Federal de Minas Gerais – UFMG, Campus Montes Claros, Montes Claros/MG, Brasil

ABSTRACT

The aim of this study is to evaluate the free and adsorbed water flow in short logs of *Eucalyptus urophylla* and *Corymbia citriodora* clones. 40 cm long, short logs were extracted from the base of the trees. Three trees each of *C. citriodora* and *E. urophylla* (A and B clones) were used. 27 logs were debarked and dried to achieve stabilization of mass. Free water (FWFR), adsorbed water (AWFR) and total water (TWFR) flow rates, and basic density were calculated. FWFR was greater than TWFR, which was superior to AWFR. The B clone wood showed a higher FWFR value and a lower AWFR value when compared to the other materials. On the other hand, the A clone wood showed a higher TWFR than the other materials. The TWFR was inversely proportional to density.

Keywords: drying, free water, adsorbed water, moisture, basic density.

1. INTRODUCTION

The relation between water and wood has been scientifically studied for over a century, focusing on softwoods (Engelund et al., 2013). The greater importance of hardwoods in recent years, such as those from the *Eucalyptus* genus, has led to increased studies on the water–wood relationship in these species (Barbosa et al., 2005; Klitzke & Batista, 2010).

Water in hardwood stems mainly flows through vessels and pit pairs (Siau, 1971). Its movement in wood is complex, given that this occurs during liquid and gas phases (Kollmann & Côté, 1968), depending on moisture levels. Based on the Hagen-Poiseuille's Law, free water flow is caused by the capillary 63.23 forces. In turn, the movement of the water in gaseous form (vapor) and adsorbed occurs via the cell wall by diffusion, due to the moisture gradient (Kollmann & Côté, 1968; Siau, 1971).

Several studies have evaluated the water outlet of the *Eucapyptus*, mainly in lumber (Barbosa et al., 2005; Jankowsky & Santos, 2005; Klitzke & Batista, 2010; Sepulveda-Villarroel et al., 2015; Latorraca et al., 2015). Publications on the drying of *Eucalyptus* logs began in the 1980s, with studies of the effect of time on wood drying (Vital et al., 1985). Other studies were conducted to evaluate the influence of diameter and bark on wood drying (Rezende et al., 2010; Pertuzzatti et al., 2013), the relationship between drying and wood density (Zanuncio et al., 2015), the effect of moisture on energy and density (Brand et al., 2011; Zanuncio et al., 2013), and the effect of anatomy on water flow (Monteiro et al., 2017). Most studies on drying focused on the production of energy, mainly for charcoal production.

Log drying is crucial for a more efficient use of wood energy. Freshly cut logs present a high moisture content, which prevents their use for energy, such as in charcoal production, where wood should have a moisture content below 30% (Brand et al., 2011). Swithenbank et al. (2011), reported that the net calorific value of wood dropped by 2 $MJ.Kg^{-1}$, with every 10% moisture increase. Additionally, high moisture in wood reduced the gravimetric yield of carbonization, given that part of the wood is burned for water removal (Rousset et al., 2011).

Understanding the movement of free water and adsorbed water on logs may help to select more permeable genetic material, resulting in less storage time in the field and higher energy density in wood. Rezende et al. (2010), report on *Eucalyptus* drying rates, which are higher in the first three weeks. Zanuncio et al. (2015), found a moisture content greater than 30% in *Eucalyptus* and *Corymbia* logs after 90 days of drying. The water evaporated depends on factors such as anatomy, density, and piece dimensions (Rezende et al., 2010; Monteiro et al., 2017; Hoang et al., 2015), as well as environmental factors such as temperature, relative humidity and wind speed (Rémond et al., 2013). Few studies have assessed water flow, above and below the fiber saturation point, or the behavior of the drying curve in Round wood. Therefore, the aim of this study is to evaluate free and adsorbed water flow rates in *C. citriodora* and *E. urophylla* short logs.

2. MATERIAL AND METHODS

The seven-year old clonal *E. urophylla* trees and seminal *C. citriodora* trees used in this study came from plantations located in the city of Paraopeba, MG, Brazil, and Belo Oriente, MG, Brazil, respectively (Table 1).

After tree felling, three logs approximately 40 cm long were taken from the base of each tree. Additionally, approximately 5 cm thick disks were extracted from between the logs, to determine basic density. The first drying measurement of the logs was taken immediately after the felling, debarking, and cross-section waterproofing using asphalt emulsion to decrease the water evaporation from this section. Soon after, the logs were stored in plastic bags, sealed, and taken to Lavras, MG, Brazil. The logs were properly stored under cover for outdoor drying control, adapting the Rezende et al. (2010), methodology.

Basic density was determined according to NBR 11941 (ABNT, 2003) using the disks. After achieving moisture content equilibrium using outdoor drying, the logs were dried in a kiln, with forced air circulation and a temperature of 105°C ± 2°C until constant weight was achieved. Later, the dry masses (moisture = 0%) were determined using an electronic scale. Log moisture was determined according to NBR 7190 (ABNT, 1997).

The moisture content of the logs used to evaluate the water flow rate in wood was calculated for each drying period. The samples were weighed on a 30kg capacity scale over 180 days. The first mass measurement was considered for initial moisture content (IM).

Table 1. Species, commercial name, number of trees, age, diameter 1.3 meters from the ground and medium commercial height of *Eucalyptus* and *Corymbia*.

Species	Symbol	# trees	*DBH (cm)	Tree height (m)
Eucalyptus urophylla	A	3	20.34	30.45
E. urophylla	B	3	19.45	29.45
Corymbia citriodora	*C. citriodora*	3	17.88	22.65

#- number; *DBH - diameter 1.3 meters from the ground, without bark.

The fiber saturation point (FSP) was considered to be 30% moisture, an average value reported by Skaar (1972). The mass considered as equilibrium moisture content (EMC) was the one at the end of drying, when it became constant.

The average time taken for free water outlet (FWT), between initial moisture content and FSP and the average time taken for adsorbed water outlet (AWT), between FSP and EMC were evaluated. The sum of FWT and AWT was used as the total drying time or the total water flow time (TWT). The fact that the drying was partial (until equilibrium moisture content) and not total (until 0% moisture) was an important point to note.

A graph that shows the log moisture loss as a function of time was generated. Different regression models were tested for free water flow, adsorbed water flow and total water flow (between initial moisture content and EMC), while a linear model, and the determination coefficient (R^2), were used because of the slight difference between the water flows.

The free water, adsorbed water and total water flow rates were determined for the logs, according to Equations 1, 2 and 3, by adapting the methodology of Barbosa et al. (2005).

a) Free water flow rate:

$$FWFR = \frac{MI - MFPS}{T2 \, x \, A} \quad (1)$$

Where, FWFR is the free water flow rate ($g.cm^{-2}.h^{-1}$); MI: wood initial mass (g); MFPS: wood mass at fiber saturation point (g); T2: free water flow (hours); *A*: exposed area for wood water outlet (cm^2).

b) Adsorbed water flow rate:

$$AWFR = \frac{MFPS - Meq}{T3 \, x \, A} \quad (2)$$

Where, AWFR is the adsorbed water flow rate ($g.cm^{-2}.h^{-1}$); MFPS: wood mass at fiber saturation point (g); Meq: wood mass at equilibrium moisture content (g); T3: adsorbed water flow rate (hours); *A*: exposed area for water outlet in wood (cm^2).

c) Total water flow rate (free and adsorbed water):

$$TWFR = \frac{MI - Meq}{T1 \, x \, A} \quad (3)$$

Where, TWFR is the total water flow rate ($g.cm^{-2}.h^{-1}$); MI: wood initial mass (g); Meq: wood mass at equilibrium moisture content (g); T1: total water flow rate (hours); *A*: exposed area for water outlet in wood (cm^2).

The average values for basic density, moisture, free water, adsorbed water and total water were calculated for each genetic material. Statistical analysis was performed for the parameters using the Analysis of Variance (ANOVA). When the analysis of variance value was significant, the Scott-Knott test was applied at 5% significance, to verify the significant differences between the mean values.

Using a digital electronic spreadsheet, *Table curve 2D*, the correlations were performed for basic density with FWFR, AWFR and TWFR. At first, the Pearson correlation coefficients (r) and significance were calculated, using the Student's *t* test for 95% probability. For significant correlations, different regression models were tested. Due to the small difference between them, the linear model and the determination coefficients (R^2) were used. A graph with a significant adjustment was shown, to illustrate the trend of the effect of density on water flow rates.

3. RESULTS AND DISCUSSION

The *C. citriodora* wood results showed a higher density and lower initial moisture content when compared to the *E. urophylla* (A and B) clones (Table 2). The lower basic density wood showed a higher volume of empty spaces, which could be filled with free water, increasing the initial moisture content in the logs. The same behavior was found by Zanuncio et al. (2015), who worked with the same genetic material logs of the same age. Values found for the basic density of the wood were consistent with the literature that studied *C. citriodora* (Lemos et al., 2012) and *E. urophylla* (Zanuncio et al., 2013) wood.

Initial moisture content (IM) and free water flow time (FWT) were higher in clone A than clone B, even though they showed close values for basic wood density (Table 2). Comparing the wood of clone A with *C. citriodora* wood, different densities were observed, with the initial moisture content (IM) of clone A being 45.4%, which was higher, and a free water flow time 33.5% higher.

The fact that the *Corymbia* logs had a smaller diameter is an important point to note. This may be an indication that to accelerate drying, the proportion and lower wood density, combined with the anatomical structures that facilitate water flow, may be more effective than lower diameters. Comparison of the results shown in Table 2, with other studies about drying, should take into account diameter and log length. Most of these studies which used 1-meter long logs found that the maximum drying time of 3,679 hours (153.3 days) was not enough to dry wood to achieve equilibrium moisture content. By way of comparison, a study performed by Zanuncio et al. (2013), evaluated the drying of different genetic material logs of *Eucalyptus* and *Corymbia* for 90 days, with 1-meter length logs. They found moisture values between 20.49 and 33.14% for logs with diameters between 12.56 and 14.23 cm and moisture between 31.13 and 61.28% for logs wth diameters between 17.88 and 20.34 cm. Rezende et al. (2010), evaluated drying of 3.6 meter *E. urophylla* logs over 80 days (1920 hours) and found 54% of moisture for logs with bark and 50% for logs without bark, which was the time spent for clone A to reach a moisture content close to fiber saturation point (Table 2).

Clone B wood presented a higher free water flow rate (FWFR), as shown in Figure 1. This result is important for the forestry biomass energy industry, given that it performs natural drying of logs. Generally, the time taken, close to 50 days for drying, is not adequate to achieve stabilization of mass (equilibrium moisture content) or in some cases a moisture close to FPS, which is the one expected for wood entering the carbonization kiln. The longest time spent for free water flow in clone A is partially due to its higher initial moisture content (Table 2). Clone A adsorbed water flow rate and *C. citriodora* adsorbed water flow rate were 1.5 times higher than the one observed in clone

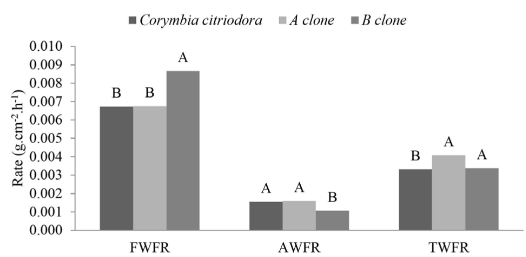

Figure 1. Water flow rates in short logs of clones A and B of *E. urophylla* and *C. citriodora*. Where, FWFR is the free water flow rate; AWFR is the adsorbed water flow rate; and TWFR is the total water flow rate. Means followed by the same letter do not differ significantly at 5% probability for the Scott-Knott test.

Table 2. Basic density, moisture, and water flow time in logs of A and B clones of *E. urophylla* and *C. citriodora*.

Genetic material	Basic density ($g.cm^{-3}$)	Moisture Content (%)		Time (hours)	
C. citriodora	0.610 A	IM	70.3 C	FWT	1327 B
		FPS	30.7 A	AWT	2239 B
		EMC	14.8 A	TWT	3566 A
A Clone (*E. urophylla*)	0.498 B	IM	102.2 A	FWT	1771 A
		FPS	30.7 A	AWT	1908 C
		EMC	14.6 A	TWT	3679 A
B Clone (*E. urophylla*)	0.523 B	IM	88 B	FWT	1123 B
		FSP	32.4 A	AWT	2537 A
		EMC	14.9 A	TWT	3660 A

IM: initial moisture content; FPS: estimated moisture content for fiber saturation point; EMC: equilibrium moisture content; FWT: free water flow time; AWT: adsorbed water flow time; TWT: total water flow time. Parameters with means followed by the same letter do not differ significantly at 5% probability for the Scott-Knott test.

B (Figure 1). The fact that the clone A and *C. citriodora* woods showed no statistical differance for free water flow rate and adsorbed water flow rate even though they showed different wood densities is an important fact to note (Table 2).

The B clone showed a higher FWFR and the lowest AWFR, which resulted in a FWFR relation 8.2 times higher than that for AWFR. In the clone A and *C. citriodora* woods, the FWFR was 4.2 and 4.3 times greater than the AWFR, respectively (Figure 1). The fact that the AWFR outlet is lower when compared to FWFR has been widely reported in the literature, mainly for coniferous wood (Kollmann & Côté, 1968; Siau, 1971; Engelund et al., 2013). Free water moves mainly in a liquid state, because of the capillary forces, based on Hagen-Poiseuille's law. In this phase, water removal uses little energy (Kollmann & Côté, 1968). Water desorption occurs because of the cell wall's moisture gradient, based on the diffusion phenomenon. In liquid and gaseous states, it spends more energy, given that the timber-water connection is maintained by stronger hydrogen bonds and the attraction between them needs to be overcome for the output of the water molecule.

The *E. urophylla* clones showed higher flow rates of the water (TWFR), as in Figure 1. This result may reinforce the choice of these clones by the bioenergy industry, given that the clone A, even though it shows higher initial moisture content, will not necessarily result in more time spent by the log in the drying yard. The superior drying rates in *E. urphylla* wood compared to *C. citriodora* was also reported by Zanuncio et al. (2013) and Zanuncio et al. (2015).

The drying of the three materials was constant over time, where two distinct phases could be noticed: below and above fiber saturation point (Figure 2). The same behavior was found by Jankowsky & Santos (2005), for the drying rate, as a function of moisture curve behavior. Free water loss occurred rapidly and constantly until the fiber saturation point. Thereafter, the adsorbed water loss remained constant, yet at a slower rate. During log drying, the clone A wood lost 3.7kg of water, the *C. citriodora* wood lost 2.6kg and the clone B wood lost 2.5 kg.

The water as a function of time estimation can be calculated by linear regression, for total drying, free water outlet, and adsorbed water outlet (Table 3). The highest determination coefficient values (R^2) occurred for free water loss, adsorbed water loss and total water loss showing values greater than 0.95; 0.87, and 0.87, respectively. Using a regression model that considers free water loss to estimate moisture, can improve the process of the forest biomass energy in industry. These industries generally use logs with a moisture content above the FPS and estimate moisture as a function of total drying.

Overall, clone B showed the lowest R^2 values for water loss for all the kinds of water studied. The values found were close to those reported in the literature for

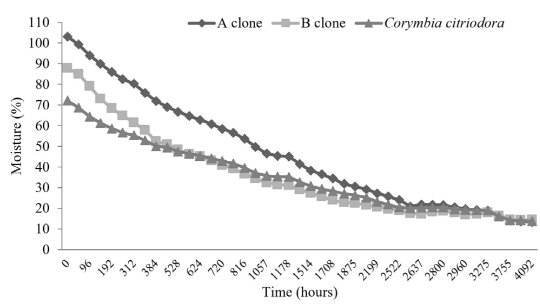

Figure 2. Average weight loss curves of short logs from *E. urophylla* and *C. citriodora* clones.

Table 3. Regression model for moisture as a function of time for free water flow rate, adsorbed water flow rate, and total water flow rate of *Eucalyptus* and *Corymbia* short logs.

Species	Water flow	Estimated model	R^2
A clone	Total	M = -2.0661T + 92.059	0.96
	Free	M = -2.6829T + 99.609	0.99
	Adsorbed	M = -0.0077T + 28.461	0.95
Corymbia citriodora	Total	M = -1.2756T + 63.464	0.96
	Free	M = -1.6984T + 68.385	0.97
	Adsorbed	M = -0.0062T + 28.524	0.95
B clone	Total	M = -1.5612T + 70.256	0.87
	Free	M = -2.7181T + 83.038	0.95
	Adsorbed	M = -0.0048T + 25.525	0.87

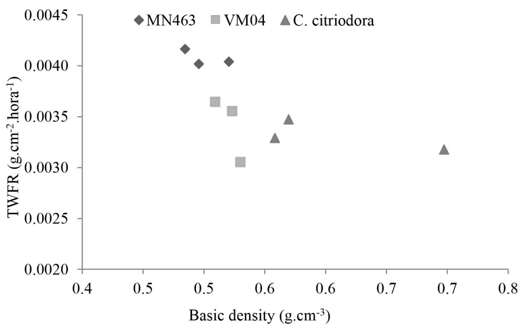

Figure 3. Relation between total drying and basic wood density of clones A and B of *E. urophylla* and *C. citriodora*.

Eucalyptus log drying. As an example, Rezende et al. (2010) found an R^2 value equal to 0.98 for logarithmic regression of log drying for 80 days and final moisture content above FSP. Jankowsky & Santos (2005), found a linear regression R^2 greater than 0.96 for the drying rate as a function of free water flow moisture and adsorbed water flow moisture.

Correlation between the basic density of wood and the water flow rate (FWFR, AWFR, and TWFR), in all genetic materials, showed a significant correlation only for the total water flow rate (TWFR), with a Pearson linear correlation value of -0.63 (Figure 3). The negative correlation coefficient value (r) was due to the inverse relationship between basic wood density and its porosity and the flow rate (Siau, 1971). The r value was lower than that found by Zanuncio et al. (2015), who observed r values between -0.765 and -0.870 for different diameter drying logs and calculated only the total drying rate (%/day). Faster total drying tends to occur in less dense wood materials. Therefore, clones A and B of *E. urophylla* showed the lowest basic density values (Table 2) when compared with *C. citriodora* wood. Therefore, those clones tended to show the highest total drying rate values.

4. CONCLUSION

The results of water flow in *Eucalyptus* and *Corymbia* wood show that:

The free water flow rates (FWFR) were greater than the total water flow rates (TWFR). The total water flow rates were higher than the adsorbed water flow rates (AWFR). The clone B wood showed a higher FWFR and a lower AWFR. On the other hand, the clone A wood showed a higher TWFR value;

The log moisture content can be estimated by linear regression for all genetic materials, for total drying, free water flow rate, and adsorbed water loss;

The TWFR was inversely proportional to basic density. Some of these results showed direct industrial application, mainly as indicators for genetic materials as a function of water flow below and above FPS, for faster drying in the field or in a carbonization kiln, for example, as well as being easier for chemical preservation and reagent wood treatment.

SUBMISSION STATUS

Received: 12 july, 2017
Accepted: 21 july, 2017

CORRESPONDENCE TO

Thiago Monteiro
Setor de Ciências Agrárias, Departamento de Engenharia e Tecnologia Florestal, Universidade Federal do Paraná – UFPR, Av. Pref. Lothario Meissner, 632, CEP 80210-170, Curitiba, PR, Brasil
e-mail: thiago.monteiro@ufpr.br

REFERENCES

Associação Brasileira de Normas Técnicas – ABNT. *NBR-7190: Projeto de estruturas de madeira*. Rio de Janeiro: ABNT; 1997.

Associação Brasileira de Normas Técnicas – ABNT. *NBR-11941: Madeira: determinação da densidade básica*. Rio de Janeiro: ABNT; 2003.

Barbosa CG, Lima JT, Rosado SCS, Trugilho PF. Elaboração de programa de secagem para madeiras de clones de híbridos de *Eucalyptus* spp. *Revista Ceres* 2005; 11(1): 40-48.

Brand MA, Muñiz GIB, Quirino WF, Brito JO. Storage as a tool to improve wood fuel quality. *Biomass and Bioenergy* 2011; 35(7): 2581-2588. http://dx.doi.org/10.1016/j.biombioe.2011.02.005.

Engelund ET, Thygesen LG, Svensson S, Hill CAS. A critical discussion of the physics of wood–water interactions. *Wood Science and Technology* 2013; 47(1): 141-161. http://dx.doi.org/10.1007/s00226-012-0514-7.

Hoang VH, Nagasaki S, Kawabata Y, Wajima T, Nakagome H. Drying mechanism of unutilized cedar logs as a source of heating fuel. *International Journal of Chemical Engineering and Applications* 2015; 6(4): 285-288. http://dx.doi.org/10.7763/IJCEA.2015.V6.498.

Jankowsky IP, Santos GRV. Drying behavior and permeability of *Eucalyptus grandis* lumber. *Maderas. Ciencia y Tecnología* 2005; 7(1): 17-21.

Klitzke RJ, Batista DC. Ensaio de taxa de secagem e escore de defeitos para a predição da qualidade de secagem convencional da madeira de *Eucalyptus. Scientia Forestalis* 2010; 38(85): 97-105.

Kollmann FP, Côté WA Jr. *Principles of wood science and technology*. Berlin: Springer-Verlag; 1968. http://dx.doi.org/10.1007/978-3-642-87928-9.

Latorraca JVF, Dias AF Jr, Silva GC, Pace JHC, Carvalho AM. Anelamento e vaporização de toras visando otimização do processo de secagem da madeira de Eucalipto. *Agrária* 2015; 10(2): 273-279. http://dx.doi.org/10.5039/agraria.v10i2a4601.

Lemos ALF, Garcia RA, Lopes JO, Carvalho AM, Latorraca JVF. Madeira de *Corymbia citriodora* (Hook.) K.D. Hill & L.A.S. Johnson sob aspectos físicos e anatômicos como fatores qualitativos. *Floresta e Ambiente* 2012; 19(1): 1-8. http://dx.doi.org/10.4322/floram.2012.001.

Monteiro TC, Lima JT, Hein PRG, Silva JRM, Trugilho, PF, Andrade HB. Efeito dos elementos anatômicos da madeira na secagem das toras de *Eucalyptus* e *Corymbia*. *Scientia Forestalis* 2017; 45(115): 493-505. http://dx.doi.org/10.18671/scifor.v45n115.07.

Pertuzzatti A, Trevisan R, Fioresi T, Rabuske JE, Trautenmüller AV, Motta CI, et al. Influência do diâmetro das toras na secagem ao ar livre de *Eucalyptus globulus* Labill. *Ciência da Madeira* 2013; 4(2): 191-201. http://dx.doi.org/10.12953/2177-6830.v04n02a05.

Rémond R, De La Cruz M, Aléon D, Perré P. Investigation of oscillating climates for wood drying using the flying wood test and loaded beams: need for a new mechano-sorptive model. *Maderas. Ciencia y Tecnología* 2013; 15(3): 269-280.

Rezende RN, Lima JT, Silva JRM, Napoli A, Andrade HB, Faria ALR. Air drying of logs from an *Eucalyptusurophylla* clone for carbonization use. *Revista Ceres* 2010; 16(4): 565-572.

Rousset P, Figueiredo C, Souza MD, Quirino W. Pressure effect on the quality of *Eucalyptus* wood charcoal for the steel industry: a statistical analysis approach. *Fuel Processing Technology* 2011; 92(3): 1890-1897. http://dx.doi.org/10.1016/j.fuproc.2011.05.005.

Sepulveda-Villarroel V, Perez-Peña N, Salinas-Lira C, Salvo-Sepulveda L, Elustondo D, Ananias RA Development of moisture and strain profiles during pre-drying of *Eucalyptus nitens*. *Drying Technology* 2015; 34(4): 428-436. http://dx.doi.org/10.1080/07373937.2015.1060490.

Siau JF. *Flow in wood*. Syracuse: Syracuse University Press; 1971.

Skaar CJ. *Water in wood*. Syracuse: Syracuse University Press; 1972.

Swithenbank J, Chen Q, Zhang X, Sharifi V, Pourkashanian M. Wood would burn. *Biomass and Bioenergy* 2011; 35(3): 999-1007. http://dx.doi.org/10.1016/j.biombioe.2010.12.026.

Vital BR, Della Lucia RM, Valente OF. Estimativa do teordeumidade de lenha para carvão em função do tempo de secagem. *Revista Árvore* 1985; 9(1): 10-27.

Zanuncio AJV, Monteiro TC, Lima JT, Andrade HB, Carvalho AG. Drying biomass for energy use of *Eucalyptus urophylla* and *Corymbia citriodora* logs. *BioResources* 2013; 8(4): 5159-5168. http://dx.doi.org/10.15376/biores.8.4.5159-5168.

Zanuncio AJV, Carvalho AG, Silva LF, Lima JT, Trugilho PF, Silva JRM. Predicting moisture content from basic density and diameter during air drying of *Eucalyptus* and *Corymbia* logs. *Maderas. Ciencia y Tecnología* 2015; 17(2): 335-344.