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BASIC DENSITY IN THE DRYING PROCESS OF *EUCALYPTUS UROPHYLLA* AND *PINUS CARIBAEA* WOOD

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The freshly cut wood has large amount of water. Wood drying is essential for timber production, regardless of its final use. Thus, the objective of this study was to evaluate the relationship between density and drying of *Eucalyptus urophylla* and *Pinus caribaea* wood. Five trees per species were selected and a central plank was removed to prepare the samples (5 × 5 × 15 cm). These samples were saturated, cubed and subjected to drying in a climatic chamber until reaching equilibrium moisture content, and subsequently oven dried at 103 °C, to obtain dry mass. The relationship between density and wood drying was assessed using linear regression models and coefficient of determination. The basic density was inversely proportional to the drying parameters above the fibre saturation point, and directly proportional to the number of drying days between the fibre saturation point and achieving equilibrium moisture content. The linear regression models estimated the maximum moisture content, water loss in the first three days, drying rate, days to reach the fibre saturation point and days between the fibre saturation point and equilibrium moisture content through wood density, with a coefficient of determination higher than 0.90, 0.54, 0.58, 0.73 and 0.45, respectively.

Keywords: Adsorption water, free water, wood physics, wood science, wood–water interactions

INTRODUCTION

The forestry sector represents 1.3% of the gross national product (GNP) of Brazil, generating R$12 billion in taxes and 500 thousand direct jobs (IBÁ 2019). *Pinus* and *Eucalyptus* plantations in Brazil are the most productive in the world generating raw material for cellulosic pulp, energy, panels, sawn wood and other products (Bernstad Saraiva et al. 2017, Ferro et al. 2018, Jesus et al. 2018, IBÁ 2019, Scolforo et al. 2019). Wood drying is necessary in all these production processes, often limiting its use (Zanuncio et al. 2013, Yang & Liu 2018).

Wood moisture in a freshly harvested tree can reach over 200% on a dry basis (Glass & Zelinka 2010, Resende et al. 2018). Free water is connected by capillary bonds in the empty wood spaces, such as lumens, while adsorption water is connected by hydrogen bonds in the hydrophilic sites of the cell wall (Kollmann & Côté 1968). These forms of interaction between water and wood require different amounts of energy to reduce moisture. The wood drying speed is not homogeneous, depending on different variables, such as temperature, air circulation and relative humidity, in addition to intrinsic wood characteristics (Zanuncio et al. 2016; Zhao & Cai 2017, Nascimento et al. 2019, Shen et al. 2020).

Basic density is the most studied wood parameter, indicating the ratio between the dry mass and its saturated volume (Kollmann & Côté 1968). This parameter is related to the number of empty spaces in the wood, maximum moisture content and drying speed (Zanuncio et al. 2013). The density will determine the amount of water mass that will be removed during drying, also affecting the diffusion through the woody material. High wood density values generally, imply slower water loss due to fewer empty spaces (Yang and Liu, 2018). The pearson's correlation coefficient between basic density and initial moisture content, drying rate and final moisture, after 94 days drying, was -0.882, -0.861 and -0.831 for *Eucalyptus* and *Corymbia* logs, respectively (Zanuncio et al. 2015). The effect of basic density on the drying of each species and its relationship with free water flow and adsorption through regression models need be evaluated. This information is important for studies on moisture prediction based on wood quality, facilitating the control of the drying process.

Thus, wood drying is a process used regardless of its end use, being influenced by the quality of the material. The objective of this study was to evaluate the relationship between density and moisture of *Eucalyptus urophylla* and *Pinus caribaea* wood during the drying process.

MATERIALS AND METHODS

Eucalyptus urophylla and *P. caribaea* wood was obtained from three 15-year-old trees of each species. After harvesting, a log was removed between 1.3 and 2.5 meters above ground level. Thirty samples (5 × 5 × 15 cm in the radial × tangential × longitudinal direction) were obtained per species from different radial positions to guarantee a diversity of basic densities (Figure 1).

The samples were saturated to constant mass and subjected to drying in a climatic chamber with 50% relative humidity at 23 °C, until equilibrium moisture content. The samples were weighed daily over 65 days, to monitor moisture loss, and then kiln dried at 103 °C to obtain the wood dry mass. The wood moisture was determined with the equation:

$$M\ (\%) = [(Wm - Dm)/Dm] \qquad (1)$$

where M (%) = wood moisture, Wm = wet mass of the sample and Dm = dry mass of the sample.

The basic density was determined by the ratio between the dry mass and saturated volume according to NBR 11941: 2003 (ABNT 2003).

Moisture loss curves were obtained during the drying process for *E. urophylla* and *P. caribaea* samples. The density values for each species were stratified into three intervals, with the average of the 10 lowest, intermediate and highest values in the three curves. The free water drying rate was calculated using the formula:

$$FW = [(Ms - 30)/t] \qquad (2)$$

where FW= free water drying rate, Ms = moisture content in saturated sample (%) and t = drying time in days to reach the fibre saturation point. The value 30 refers to the fibre saturation point (PSF), equivalent to 30% on a dry basis. The drying rate of the adsorption water was calculated with the formula:

$$AW = [(30 - EM)/t] \qquad (3)$$

where AW = adsorption water drying rate (%/day), EM = equilibrium moisture content of the sample (%), t = days of drying between fibre saturation point (FSP) and equilibrium moisture content (%).

The relationship between density and moisture of the saturated samples, moisture losses in the first three days, period to reach fibre saturation point (30%), free water drying rate

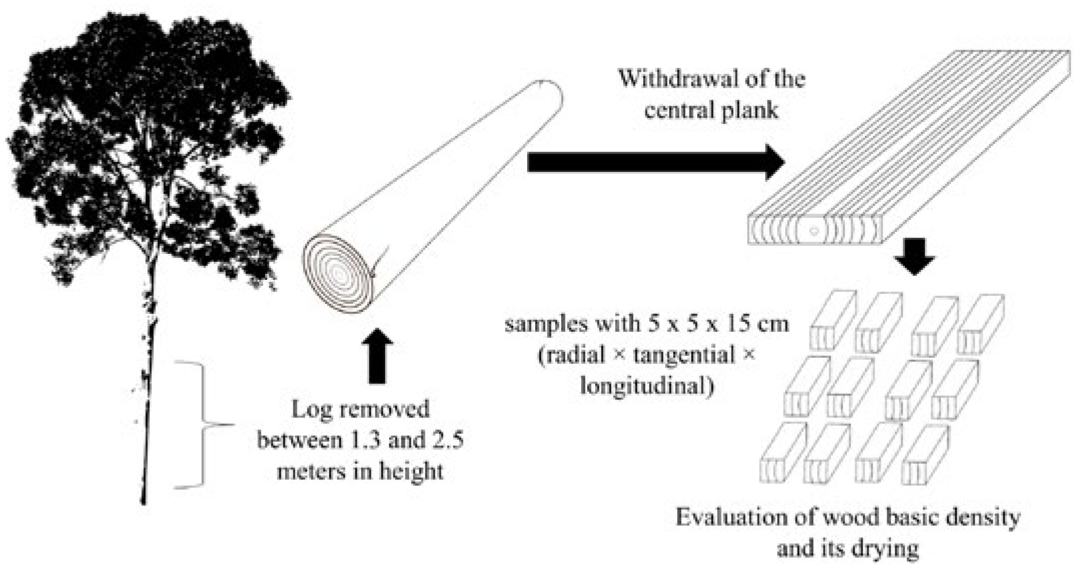

Figure 1 Simplified diagram of sampling to evaluate wood density and its drying

and adsorption water drying rate was evaluated using linear regression models and the coefficient of determination. The evaluations were carried out separately per species.

RESULTS AND DISCUSSION

The basic density of *E. urophylla* and *P. caribaea* samples varied from 455 to 535 kg m^{-3} and from 290 to 450 kg m^{-3}, respectively (Figure 2). The higher basic density of *Eucalyptus* wood is the result of its anatomical structure, with the hardwoods having higher percentage of cell wall, especially compared to fibres and tracheids (Panshin & De Zeeuw 1980). The basic density values of *E. urophylla* and *P. caribaea* woods were similar to those found in other studies, 420 to 600 kg m^{-3} for species of the genus *Eucalyptus* and 310 to 510 kg m^{-3} for those of *Pinus* (Martinez-Meier et al. 2011, Deng et al. 2014, Melo et al. 2018, Ribeiro et al. 2019, Costa et al. 2020).

The moisture loss varied throughout the drying period of the *E. urophylla* and *P. caribaea* woods, being greater at the beginning and falling until equilibrium moisture content (Figure 2). The moisture loss of *E. urophylla* and *P. caribaea* samples was higher than 15% in the first three days. This high value, in relation to the total period evaluated, is associated with the large quantity of free water in the surface area of the samples and a higher humidity gradient in relation to the surrounding atmosphere, favoring the passage of water from wood to air at an accelerated speed (Li et al. 2017, Fredriksson 2019). The reduction in the drying rate, over time, is due to the remaining free water inside the sample, a region close to the pith, making it difficult to reach the surface and evaporate into the atmosphere (Engelund et al. 2013). The adsorption water in the wood is the last to be lost as its hydrogen bond with the cell wall, thereby hampering its removal and further reducing the drying rate, and tending towards zero when the wood reaches equilibrium moisture content. This behavior was observed for all wood samples, but with a variable period according to the drying stage, species and wood density.

The basic density was inversely proportional to the drying parameters above the fibre saturation point (Figure 3).

The initial average moisture content of the *Eucalyptus* and *Pinus* wood was 123 and 200%, with lower value for the samples with higher density. A higher wood density reduces the empty spaces inside the fibres and vessel elements, and consequently the water content (Kollmann & Côté 1968). The amount of free water in relation to adsorption water was higher in all samples, and the reduction of empty spaces, by increasing the basic density, reduced the amount of free water. The inverse relationship between density and moisture of saturated wood has also been reported for *E. urophylla* and *Corymbia citriodora* logs, and *E. saligna* sawn wood (Zanuncio et al. 2015, Soares et al. 2016). The linear regression models predict the initial moisture of the samples, based on the basic density with high precision, with a coefficient of determination of 0.9073 and 0.9555 for *E. urophylla* and *P. caribaea* samples, respectively. The large amount of water

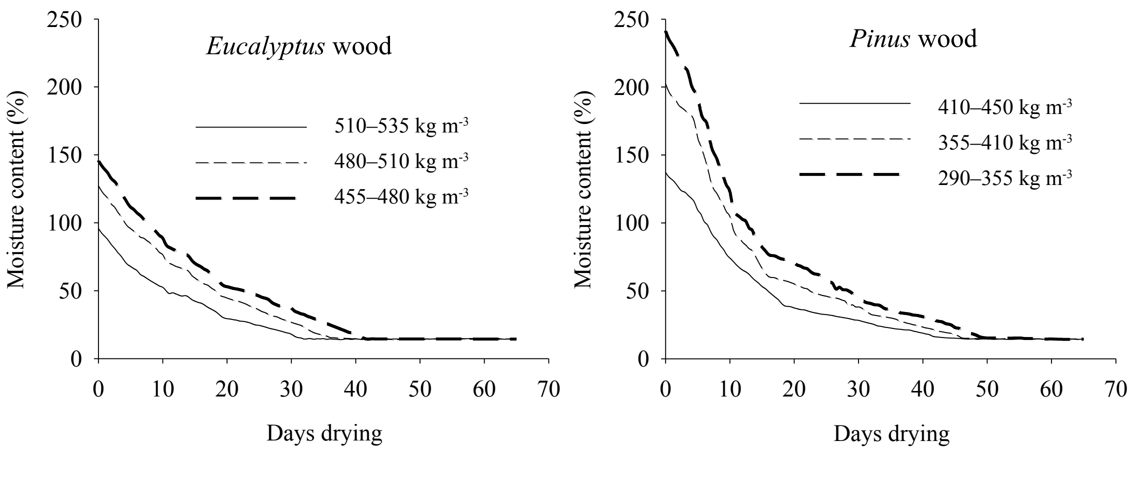

Figure 2 Drying curve of *Eucalyptus urophylla* and *Pinus caribaea* samples with different densities

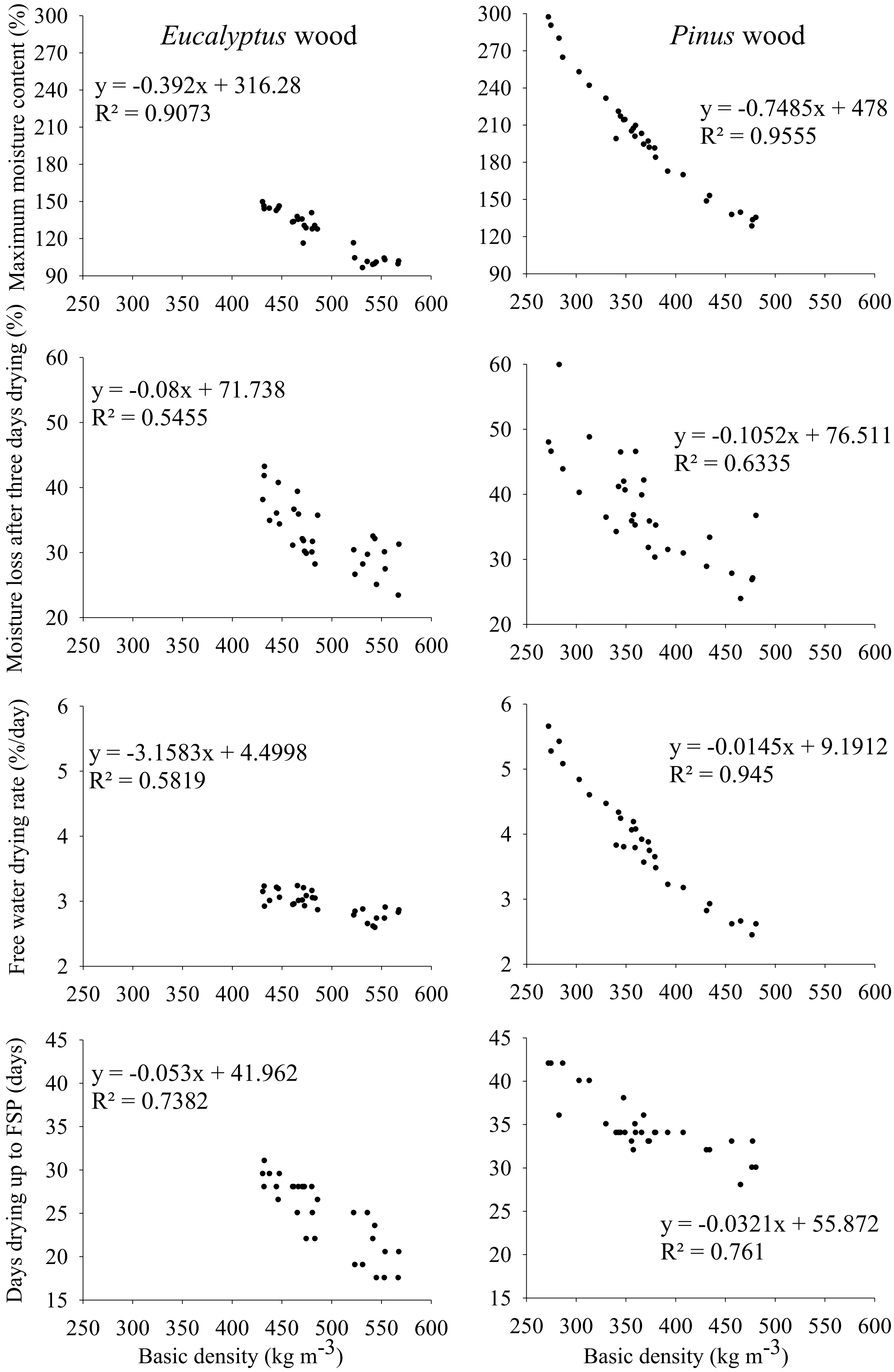

Figure 3 Relationship between density and drying of *Eucalyptus urophylla* and *Pinus caribaea* wood above the fibre saturation point; R^2 = coefficient of determination of linear regression models, SPF = fibre saturation point

in the wood limits its use for energy purposes and as sawn wood, and increases its biodeterioration, making drying important in wood processing (Soares et al. 2016, Marques et al. 2018, Thybring et al. 2018, Melo et al. 2019).

The free water flow varied with wood density, with greater losses in the first three days and a higher drying rate to fibre saturation point for the samples with lower density. The coefficient of determination of linear regression models was greater than 0.54 and 0.63 in *E. urophylla* and *P. caribaea* wood, respectively. The higher initial moisture, resulting from the greater volume of empty spaces in the wood samples with lower density, increased the moisture gradient of the wood with the surrounding atmosphere, favoring water removal. In addition, the movement of water inside the wood occurs mainly by diffusion, crossing the cell wall in liquid form, which demands more time to cross the cell lumen in the form of steam (Engelund et al. 2013). The wall fraction is directly proportional to basic density, delaying the transportation of water by diffusion of the fibres, and therefore the drying rate (Barotto et al. 2017). The highest free water drying rate in lower density woods was reported for *E. urophylla* and *Populus tremula* × *P. tremuloides* wood (Zanuncio et al. 2015, Hytönen et al. 2018).

The *E. urophylla* and *P. caribaea* samples reached fibre saturation point between 18 and 30, and 28 and 40 days of drying, respectively, with the first species presenting a higher density. The *E. urophylla* wood, which is denser than *P. caribaea* wood, reached fibre saturation point first due to its lower initial moisture. The phenomenon of higher density wood reaching fibre saturation point first was also reported for *Cryptomeria japonica, E. grandis* and *Tsuga heterophylla* lumber and *Eucalyptus* and *Corymbia* logs (Mugabi et al. 2010, Watanabe et al. 2012, Zanuncio et al. 2015, Bernstad Saraiva et al. 2017).

The linear regression models estimated the drying time between PSF (30% humidity) and equilibrium moisture content, with a coefficient of determination of 0.53 and 0.45 for *E. urophylla* and *P. caribaea* wood, respectively (Figure 4). The greater cell wall volume of samples with higher density hampers water diffusion (França et al. 2019). Additionally, differences in permeability between hardwoods and softwoods associated with differences between latewood and early wood, types of pith membranes, and between heartwood and sapwood regions, can influence the conduction of adsorption water (Barbosa et al. 2005).

CONCLUSIONS

The wood drying rate was variable, with greater water loss in the first days and a decrease until equilibrium moisture content for *E. urophylla* and *P. caribaea* wood, with higher density for *E. urophylla.* The basic density and drying parameters above FSP were inversely correlated. The best models to predict drying parameters from density were obtained with the relationship between the maximum moisture content and the period (in days) to reach fibre saturation point, with a

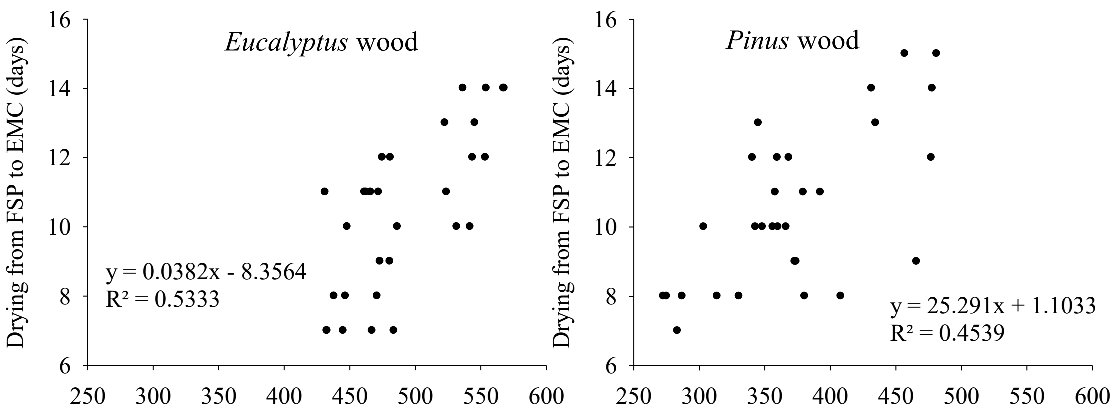

Figure 4 Drying days between the fibre saturation point and equilibrium moisture content of *Eucalyptus urophylla* and *Pinus caribaea* wood; R^2 = coefficient of determination of linear regression model, FSP = fibre saturation point, EMC = equilibrium moisture content

coefficient of determination of 0.90 and 0.73, respectively. The drying period between FSP and EMC was longer for samples with higher density. The basic density and drying parameters of wood were related throughout the evaluation period. Therefore, wood density must be considered for drying procedures.

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