Floram Floresta e Ambiente

Floresta e Ambiente 2019; 26(3): e20180353
https://doi.org/10.1590/2179-8087.035318
ISSN 2179-8087 (online)

Review Article

Wood Science and Technology

Do the Growing Conditions of Trees Influence the Wood Properties?

Maria Fernanda Vieira Rocha[1], Taís Regina Lima Abreu Veiga[1], Bruno Charles Dias Soares[1], Ana Clara Caxito de Araújo[1], Ana Márcia Macedo Carvalho[2], Paulo Ricardo Gherardi Hein[1]

[1]Universidade Federal de Lavras – UFLA, Lavras/MG, Brasil
[2]Universidade Federal de Viçosa – UFV, Viçosa/MG, Brasil

ABSTRACT

Currently, there is a little and sparse information about how the growing conditions influence the spatial variation of wood along the stem. Thus, the aim of this study was to compile the knowledge from literature in a manuscript for better understanding to what extent the growing conditions influence the spatial variation of wood properties in *Eucalyptus* plantations. The wood characteristics may present variations in their properties and can be caused by both genetic and environmental factors. However, how genetic and environmental factor acts on wood variation along the trunk is still unclear. Another point is that even with new genetic breeding programs, the mechanical properties of wood have not been considered in these programs, since the selection of new material is always based on the growing rate, cellulose and lignin content and wood density.

Keywords: wood quality, spatial variation, NIR, resonance.

1. INTRODUCTION

Wood plays a very important role in the world because it is an environmentally sustainable material and a renewable resource. The deforestation of natural forests is causing serious economic and environmental problems, not only locally, but also globally. The establishment of forest plantations for providing raw material with adequate quality for pulp and paper production, energy products, wood panels and sawn wood industry, is the key to reducing deforestation of natural forests. The forest sector has played a major role as source of income for the national economy, generating products intended for both direct consumption and export.

Eucalyptus has been the focus of several genetic breeding studies due to its rapid growth and good adaptation to climatic and soil conditions of Brazil, which makes it an important specie for the reduction of native species deforestation. However, for each intended use, whether pulp and paper, charcoal production, and others, wood requires specific, sometimes contrasting features. The wood characteristics may present variations in their properties and performance in specific applications, and can be caused by both genetic and environmental factors. But, how genetic and environmental factor acts on wood variation along the trunk is still unclear. In this context, studies have been carried out aiming to better understand how environmental components, e.g. planting density, influence wood quality.

However, there is little and sparse information about how the growing conditions influence the spatial variation of wood along the stem, since most studies have analyzed the radial or longitudinal variation in only one environment. Thus, it is necessary to compile the little and sparse knowledge from literature in a manuscript for a better analysis of to what extent growing conditions influence the spatial variation of wood properties in *Eucalyptus* plantations, which may encourage further research in this area.

2. IMPORTANCE OF *EUCALYPTUS* WOOD AS RAW MATERIAL

Considering the wide variety of *Eucalyptus* species and clones cultivated in Brazil, it is necessary to search for new information on wood properties, so that the selection of genetically superior material may be successful (Pereira et al., 2012).

The term wood quality is widely used, but cannot be defined in one specific way. Wood quality is defined as the attributes that make logs and lumber valuable for a particular end use. In the pulp and paper production, low-density wood combined with long fibers results in collapsible, easy bonding fibers that exhibit low porosity and high strength. Conversely, structural lumber manufacturing requires high-density wood, small knots, and straight grain characteristics to ensure high-quality product (Joza & Middleton, 1994).

According to Downes & Raymond (1997) and Trugilho et al. (2007) the knowledge on the heterogeneity of *Eucalyptus* woods is fundamental to indicate their correct use, predict their physical-mechanical behavior and establish an appropriate sampling method.

Radial and longitudinal variation in wood properties observed along the trunk and can be primarily due to differences in the proportion of juvenile and mature wood (Malan & Hoon, 1992).

According to Santos et al. (2011), high density, low ash levels, and high lignin content are characteristics that should be considered as wood quality indices for charcoal production.

Considering the use of *Eucalyptus* as lumber, Zobel (1981) stated that one of the major problems is related to the existence of growing tensions, and the highest prevalence occurs in juvenile wood. Growth stress forces are internally generated in the growing tree, it may cause wood defects such as cracks, warping and reduction in wood strength (Chafe, 1979). Growth stress is a major cause of degradation and processing problems, especially in fast-growing *Eucalyptus* wood, inducing warping and splitting of logs and boards (Panshin & De Zeeuw, 1980).

Thinking on wood use for furniture, density, volumetric shrinkage, bend strength, modulus of rupture, compressive strength, tensile strength, shear strength, stiffness, and other wood properties should be taken into account (Serpa et al., 2003). According to Dias et al. (2013), lower density woods are susceptible to increased pulling of chips and presence of fuzzy grains, which interfere with roughness results. Roughness is an important parameter used in the evaluation of surface quality. Dias et al. (2013) affirmed that the *Eucalyptus* species analyzed in their work presented satisfactory quality for the furniture industry, based on the analysis of wood usinability parameters.

3. EFFECT OF SILVICULTURE AND MANAGEMENT ON WOOD QUALITY

3.1. Tree growth

Many silvicultural operations can affect tree growth such as plant spacing, fertilization, pruning, thinning and others (Zobel, 1992).

At shorter spacing level, stand leaf areas and biomass develop more rapidly and the site is "fully occupied" sooner. Early stand growth rates will be faster at shorter spacing, and peak current or mean annual increments can occur sooner (Stape & Binkley, 2010; Chen et al., 2011).

Trees with large crowns produce low-quality wood because they produce more auxin (Larson, 1962, Sundberg et al., 2000). Auxins produced in stem apices, such as indolic-3-acetic acid (IAA), have been linked to the type (size and thickness) of wood cells formed (Little & Pharis, 1995), so that higher IAA concentrations result in larger cell diameters with thinner cell walls, which is known as earlywood (Larson, 1962; Sundberg et al., 2000).

At tree level, the more intense competition for light, water and nutrients will result in smaller average tree size, but competition (e.g. for light) improves stem form and controls crown architecture by restricting branch sizes and accelerating branch sheddingrates, thereby improving wood quality (Neilsen & Gerrand, 1999; Alcorn et al., 2007; Forrester & Baker, 2012). On the other hand, larger spacing levels result in larger average tree sizes and faster individual tree growth rates (Stape & Binkley, 2010). The effect of spacing on mean tree size increases with age (Forrester et al., 2013)

According to Malan & Hoon (1992), the control of plant density, either through initial spacing or thinning or the combination of both and others factors, are silvicultural practices strongly influencing both tree growth and wood formation. Assuming that water and nutrient availability is similar, individual trees of widely spaced or thinned stock will grow faster than those planted over shorter plant spacing levels. According to the same author, rapid early growth, resulting in large core of juvenile wood, is an important consideration regardless of species involved.

Husch et al. (1972) stated that each species and each tree may need a period of time to complete its life cycle. Changes in forest growth conditions affect the amount of produced timber, dominance, mortality rate, and growth stagnation age (Sanquetta et al., 2003).

Competition for nutrients causes reduction in the increase of plant biomass, thereby trees planted in larger spacing will have increased availability of nutrients and higher available air space, or will contribute to the increase in carbon storage capacity, taking out from the atmosphere and stocked in the form of cellulose (Souza et al., 2008).

According to Balloni (1983), Cockerham (2004) and Li et al. (2007), tree diameter growth is influenced by a characteristic spacing within certain limits, i.e., the greater the spacing, the less the competition among plants and, consequently, the greater the diameter acquired by trees. Regarding tree height, Oliveira et al. (2010) reported that growth is less influenced by spacing, which may vary according to the location quality and evaluation age.

Faster growth could have two negative effects on timber quality, which normally represent the limit of silvicultural treatment: excessive ring width and excessive presence of branches (Hapla et al., 2000).

The effect of silviculture and management applied on forest planting can influence tree growth, as many studies have shown and some examples are shown in Table 1.

Table 1. Studies analyzing the effect of different planting spacing levels on tree growth.

Specie	Major findings	Reference
E. camaldulensis and *E. pellita*	Larger plant spacing: higher growth in diameter and root biomass of both species	Leles et al. (1998)
E. grandis and *E. saligna*	Larger plant spacing: higher diameter at BH height and higher height in both species Shorter plant spacing: higher volumetric yield (m^3/h) for *E. saligna*	Garcia et al. (1991)
P. taeda L.	Larger plant spacing: higher mean square diameter, higher volume and higher survival tree Shorter plant spacing: higher volume per ha	Leite et al. (2006)
P. taeda L.	Larger plant spacing: smaller basal area	Inoue et al. (2011)

3.2. Wood properties

For a subject such as effect of silviculture on wood properties, the only proper initial statement is that anything that causes a change in the growth pattern or form of a tree may result in changes in wood properties (Zobel & Van Buijtenen, 1989).

Fast initial growth would maximize the size of the juvenile core and thus have a significant effect on the wood properties of the stem as a whole (Malan & Hoon, 1992).

Wood properties are a function of genotype and environment (climate, site and silviculture), but can vary among individuals and be influenced by silvicultural practice, e.g., irritation, thinning, plant spacing, pruning and fertilizer application (Raymond et al. 2001).

One of the important factors driving wood property variation is growth rate (Zobel & Van Buijtenen, 1989). However, Medhurst et al. (2012) reported that the impact of reduced competition and increased diameter growth rate on the properties of eucalypt wood is not well defined or understood.

Silvicultural practices and environment are considered to be relevant factors in wood density determining the effects of ring width and cambial age on wood density. Zobel & Van Buijtenen (1989) reported that many studies on the relationship between wood density and growth rate have been carried out. The growth pattern in the irrigated treatment, which favored production of higher proportion of earlywood, resulted in wood with lower basic density compared to non-irrigated trees (Downes et al., 2006). Rocha et al. (2016) reported that larger plant spacing tends to produce trees with denser woods in *Eucalyptus*.

Furthermore, studies with different species have shown that site, silvicultural treatments such as fertilization and thinning, latitude, annual temperature, rainfall, frost and irrigation have variable influence on MFA, which can be associated with the plant growth rate (Donaldson, 2008).

Variations in wood properties depend on various factors, including silvicultural treatments applied to forest planting. Some examples of research showing these relationships are shown in Table 2.

4. SPATIAL VARIATION OF WOOD PROPERTIES ALONG STEM

Wood, whether analyzed in the radial, cross or longitudinal sections, along the stem, has variation in its chemistry (composition, relative percentages, covalent bonding, etc), as well as in mechanical,

Table 2. Studies analyzing the effect of silvicultural treatments on wood quality.

Specie	Silvicultural treatment	Major findings	Reference
Cedrusatlantica	Thinning	Larger plant spacing: the proportion of heartwood in the stem cross sections increased at all stem heights examined; mean basic density decreases with stem height in all examined stands	Hapla et al. (2000)
P. radiata	Thinning Fertilizer application	Trees that were thinned and received fertilizer treatment resulted in lower density, higher microfibril angle (MFA) and slightly lower stiffness	Downes et al. (2002)
P. radiate	Plots of different seeds Levels of thinning and pruning	Early thinning down to a final stand density of 400 stems ha^{-1} had no detrimental effect on wood stiffness; however, there are substantial adverse impacts on wood MFA and MOE at final stand densities below this level, showing that forest managers are able to influence the wood properties	Moore et al. (2015)
E. grandis x *E. urophylla*	Planting spacing Regions: irrigated and non-irrigated	Larger spacing levels: higher of lignin and hemicellulose levels Irrigated area: higher levels of extractives	Moulin et al. (2015)
E.grandis x E. urophylla	Soil slope Wind regime	Land without inclination: Higher wood density Area with higher wind regime: higher MFA and MOE variation	Hein et al. (2016)
E.grandis x *E. camaldulensis*	Planting spacing	Larger spacing: tend to produce trees with denser woods	Rocha et al. (2016)

physical and anatomical properties, being therefore considered heterogeneous material (Megraw, 1985; Savidge, 2003). This variation occurs among species, although they also occur within the same species, mainly due to age, genetic and environmental factors. Within the same species, there are significant variations in trunk height (longitudinal) and toward the bark pith (radial). Furthermore, there are differences between earlywood and latewood, heartwood and sapwood, and on a microscopic scale, among individual cells (Kollmann & Cotê, 1968).

Many silvicultural treatment can make changes on wood quality, as Paul (1963) and Megraw (1985) reported how wood density and other wood quality features that can be manipulated through silvicultural treatment. As an example, irrigation can greatly increase the latewood to earlywood ratio of temperate-zone conifers, evidently by forestalling the entry of the cambium into dormancy during the period of cambial growth in mid- to late-summer (Paul, 1963). In general, silvicultural treatments accelerating hardwood growth rate can concomitantly have an effect on wood properties.

Binkley et al. (2002) point out that the choice of arrangements and spacing unsuitable for the species can intensify competition and reduce growth homogeneity, which contribute to increase the number of trees and to lower utilization of available resources. According to Raymond (2002), wood variation, as a raw material, is a major determinant of the properties of products made from it; however, Downes et al. (2009) reported that wood property variation remains difficult to be accurately predicted, since, according to Zobel & Jett (1995), a larger proportion of this variability in wood properties is under genetic control.

There are both genetic and environmental reasons for changes on wood characteristics. The genetic makeup of trees influences both competence for growth and the physicochemical nature of tree growth. The environment in which trees grow may serve to accelerate or retard growth competencies and modify the physicochemical attributes arising during growth (Savidge, 1996).

In view of this variation, the most commonly studied property is density (Downes & Raymond, 1997) as it is easy to measure and is related to many product performance issues, such as timber stiffness, strength, pulp and paper productivity.

Variations in wood density along the stem are less consistent than those in the radial direction. As the cylinder of juvenile wood extends from the base of the stem to the top, the proportion of juvenile wood over the cross-section of the stem increases (Taylor, 2010). Variation in wood properties results from differences in the genotype of trees and environments in which plants grow (site and climate) (Malik & Abdelgadir, 2015).

Wood density has been reported to exhibit variable patterns in trees both longitudinally and radially, However, measuring this variation eucalyptus is difficult, due to the absence of annual ring structure that makes it difficult to define annual increments data. The most common trend observed is for density to increase with increasing tree height, sometimes accompanied by an initial decrease in the tree base. Where initial decrease in density is followed by increase in height, minimum density is observed at the first sampling height above the tree base (Raymond & Muneri, 2001).

Downes et al. (2009) pointed out that more recent studies have investigated tree variation (e.g. Figure 1) at high spatial resolution, allowing a better understanding of the true variability within trees.

Downes et al. (2014) analyzed the wood properties of 10-year-old trees in *Eucalyptus globulus* plantations, at three sites (unthinned, 1250 stems ha^{-1}; thinned to 600 ha^{-1} or 300 stems ha^{-1}), and nitrogen fertilizer application (0 or 250 kg ha^{-1} elemental nitrogen). They concluded that air-dry wood density, MOE (modulus of elasticity) and KPY (Kraft pulp yield) increased, on average, from pith to bark, while MFA consistently

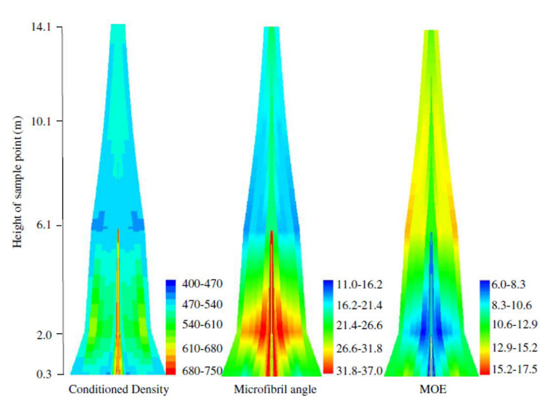

Figure 1. Tree variation density (kg m^{-3}), microfibril angle (degrees) and stiffness (MOE) (GPa) in a 140-year-old spruce. Source: (Downes, unpublished, cited by Downes et al., 2009).

decreased from pith to bark in all treatments. Radial increases in KPY and cellulose content were also found, and radial trends in wood density can in some cases be attributed to the changing dynamics of cambial activity (Drew et al., 2010). The pith-to-bark trends of increasing density and stiffness and declining MFA reported here are consistent with those of other studies on eucalypts (Medhurst et al., 2012; Wentzel-Vietheer et al., 2013).

Lima et al. (2011) evaluated the radial variation on the cellular dimensions of the wood of a 31-year-old *Tectona grandis* tree planted on three different plant spacing (3 x 1.5; 3 x 2; and 3 x 2.5). They found a positive relationship between fiber length and fiber wall thickness with radial position and a negative relation between vessel diameter and ray frequency with the radial position.

Hein et al. (2016), testing a 6-year-old *Eucalyptus grandis* x *E. urophylla* hybrids growing in three contrasting growing conditions influenced by ground slope and wind regime, found that pith-to-bark variations in wood density, MFA and MOE is more consistent than those along the trunk. Wood density, MFA and MOE have lower tree top variation because these woods were recently produced, few months before harvesting. The authors reported that the spatial variation of wood stiffness seems to be sensitive to two environmental conditions, and concluded that at the base and top of trees there was no significant effect of growing conditions on the radial variation of the wood properties considered on their study.

Antony et al. (2015) conducted a study in an attempt to identify geographical variation in loblolly pine bark and wood properties at whole-tree level and to quantify responses in whole-tree bark and wood properties following contrasting silvicultural practices that included planting density, weed control and fertilization. The authors found significant regional variation on the whole-tree bark and wood properties as the bark percentage and wood basic density showed an increase trend from pitch to bark. They conclude that the effect of different silvicultural treatments on bark and wood properties are generally absent, but a significant effect on bark percentage and basic density of both materials was observed for trees that receive intensive treatments such as early age competition control plus multiple fertilizations.

In hardwoods, MFA decreases with height, reaching minimum value at 30-50% of stem height before increasing again towards the crown, especially in *Eucalyptus* (Evans et al., 2000b). MFA remains constant with height apart from higher angles at ground level in *E. globulus* (Downes et al., 2003). In *Eucalyptus nitens*, MFA declines from pith to bark but unlike conifers, angles are much lower close to the pith, typically 15-20°. Based on average trends for 29 trees, MFA in *E. nitens* declines from 20° at the pith to 14° at the bark for 15-year-old trees. In *Eucalyptus globulus* Labill. and *E. nitens*, French et al. (2000) found angles of 0-13° with only a 5° difference between inner and outer stem regions.

Naji et al. (2014), studied the radial variation in fiber cells, vessel elements, and ray cell with the distance from the pith to bark on rubberwood (*Hevea brasiliensis*), with 9 – year–old trees, at varying stocking densities (500, 1000, 1500 and 2000 trees ha^{-1}). The results showed an increase in fiber features, vessel diameter, ray height, and ray area. Vessel density and ray density showed a decreasing trend. Ray area showed a relationship with ray density and ray height. Radial variation was explained by the effect of cambial age.

Downes et al. (2012), developed calibrations for solid wood samples, which were constructed to describe radial variation in Kraft pulp yield and cellulose content using intact *Eucalyptus globulus* Labill wood samples from three sites with contrasting annual rainfall levels. The authors concluded that pulp yield and cellulose content were higher at more productive, wetter sites and the outer wood near the cambium had pulp yield values up to 8% higher than those at the pith. On more productive sites, higher pith-to-bark increases in pulp yield were obtained, compared to drier site.

5. INFLUENCE OF PLANT SPACING ON WOOD PROPERTY VARIATIONS

According to Leles et al. (1998), plant spacing determines the time and intensity of competition among trees, which enter into competition when available resources decrease (Harrington et al., 2009); thus, spacing can affect the development and productivity of forests, especially for fast growing species.

Plant spacing plays an important role in determining wood properties, which effects are species-specific (Tong et al., 2009). Differences in wood produced at extremely wide and narrow initial spacing are less a matter of quality than quantity (Larson et al., 2001). Hart (2010) showed that with increasing plant spacing, adverse effects on wood intended for structural purposes occur. In addition, increased spacing could potentially decrease fiber length and increase knot size and frequency. A dense initial spacing can be used and subsequently reduced in stand development.

The control of stand density, either through initial spacing or thinning or a combination of both are silvicultural practices strongly influencing both tree growth and wood formation. Assuming that nutrient and water availability is similar, the individual trees of widely spaced and/or thinned stock will grow faster than crowded trees (Malan & Hoon, 1992).

A better understanding of the relationship between initial spacing and wood and the quality of end products could help improving forest management strategies required to produce quality wood and products in the future (Kang et al., 2005). The same authors concluded that initial plant spacing has a significant effect on wood density, fiber and pulp properties, and thus it is possible to improve yield and wood and pulp fiber properties of jack pine through stand density regulation. Additionally, a positive effect of pre-commercial thinning on fiber properties was also demonstrated.

In another study, Watson et al. (2003) analyzed a 38-year-old coastal western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and found that the wood density is not affected by plant spacing. At the largest spacing level, the outer wood fiber length was significantly shorter than in the four shorter spacing. Fiber coarseness and cell wall properties were similar at all tree spacing levels. Garcia et al. (1991) concluded that the basic density shows a tendency to decrease with increasing spacing, while Rocha et al. (2016) found increased density with larger spacing.

Yang & Hazenberg (1994) studying the impact of spacing on tracheid length, relative density, and growth rate of juvenile and mature wood in 38-year-old *Picea mariana* (Mill.) trees affirm that the growth rate in juvenile wood is significantly different among the different spacing levels (1.8 x 1.8, 2.7 x 2.7, and 3.6 x 3.6 m). The highest relative density, in both juvenile and mature wood was found at the shortest spacing level and have no significant difference in the relative density between the two largest spacing levels was observed. The longest fiber lengths were found at intermediate spacing, and tracheid lengths at the larger plant spacing were significantly shorter than those of the other two spacing levels.

Downes et al. (2014) worked with 10-year-old *Eucalyptus globulus* trees at three sites (unthinned, 1250 stems ha^{-1}; thinned to 600 ha^{-1} or 300 stems ha^{-1}), and nitrogen fertilizer application (0 or 250 kg ha^{-1} elemental nitrogen), and found that on the largest spacing level, trees have increased basic wood density and no changes on MFA by plant spacing and the highest MOE on the shortest spacing level. Lima et al. (2011), analyzed 31-year-old *Tectona grandis* tree on different plant spacing levels (3 x 1.5; 3 x 2; and 3 x 2.5) and concluded that fiber length, fiber wall thickness and frequency vessel were influenced by planting spacing.

Malimbwi et al. (1992) analyzed the effect of planting spacing in 19-year-old *Cupressus lusitanica* and concluded that basic density, heartwood content, modulus of elasticity, modulus of rupture and compression parallel to grain were not significantly affected by planting spacing. The same tendency was found by Ishiguri et al. (2005), who investigated the effect of planting spacing on basic wood density and length of latewood tracheids of 35-year-old *Cryptomeria japonica* D. Don.

Wood from fast-growing plantations often has physical and mechanical properties that make it less desirable than wood from older, natural stands because plantation trees contain more juvenile wood. The size of the juvenile core is related to the growth rate, which is influenced by initial spacing and the period to crown closure (Clark & Saucier, 1991). Theproperties of juvenile wood and their adverse effects on product quality and yield have been reported by many researchers (Zobel, 1981; Bendtsen, 1978). Juvenile wood is characterized by faster growth rate, lower density and strength, shorter fibers and greater microfibril and fiber angle when compared with mature wood. In addition, lignin and hemicelluloses content are higher in juvenile wood while alpha cellulose is lower (Passialis & Kiriazakos, 2004).

Planting spacing greatly affects wood quality. An increase in tree spacing adversely affects the modulus of elasticity of wood. These decreases are in a large part due to the size and number of knots developed in large spacing levels (Zobel, 1992).

6. WOOD PROPERTIES

6.1. Wood density

Wood density is widely regarded as a key trait in determining whole wood quality because it exhibits a strong correlation with other wood properties (Panshin & De Zeeuw, 1980). Due to its importance, density (basic density) is normally the first wood property to be assessed in a tree improvement program (Lima et al., 2000).

Basic wood density, defined as the mass of oven-dry wood per volume unit of wood in green condition, is a critical timber quality trait for the production of pulp, paper and sawn timber (Zobel & Van Buijtenen, 1989).

According to Kollmann & Cotê (1968), density variations are due to differences in the wood anatomical structure and amount of extractive substances per volume unit, depending mainly on tree age, genotype, site index, climate, geographical location and silvicultural treatments.

Density variations are dependent on changes in the proportion of vessels and the thickness of the cell walls of fibers. The increase in density may be the result of the increasing cell wall thickness of fibers or increase in the proportion of fibers in relation, for example, to the proportion of vessels. Conversely, an increase in the proportion of vessels with or without a decrease in cell wall thickness leads to reduction in density (Oliveira & Silva, 2003).

Wood density is very important because it is a property that directly influences many wood attributes including strength, shrinkage and pulp yields (Joza & Middleton, 1994). In a study on *Eucalyptus* trees, density alone accounted for 81% of MOE variation (Yang & Evans, 2003). Wood density has a positive relationship for both radial and tangential shrinkage but also has a negative correlation for longitudinal shrinkage (Pliura et al., 2005).

6.2. Wood stiffness

Wood stiffness, indicated by the modulus of elasticity (MOE) is an important property for structural and semi-structural wood products (Raymond, 2002).

Wood stiffness, in hardwood species, is strongly influenced by basic density (Innes, 2007; Nicholson et al., 1975), but the cellulose microfibril angle, lignin proportion and extent of spiral grain also influence on wood stiffness (Huang et al., 2003; Nicholson et al., 1975).

MOE obtained by bending is, according to Yang & Evans (2003), a mechanical property that has received considerable attention, especially in the case of wood from rapid growth commercial plantations, because these woods supply the commercial demand. Wood from these rapid growth plantations, usually contains large proportion of juvenile wood, and thus does not exhibit satisfactory mechanical properties for certain uses (Evans et al., 2000a).

Hoibo & Vestol (2010) reported that although there are several important studies on the mechanical properties of round timber of various species, information about the different mechanical properties of round logs is still deficient or nonexistent for several species and areas. The mechanical properties of wood exhibit great variation within and between trees and are difficult to be accurately described.

7. NON DESTRUCTIVE WOOD EVALUATION

Typically, wood characterization is performed by traditional and destructive analysis of samples, using specific equipment and conducted slowly, standard-based testing routines and capable of providing reliable results (Ross & Pellerin, 1994). However, this type of assessment requires long lead time between preparing samples and obtaining final values for the relevant property.

Nondestructive evaluation of the wood properties has its origin in the need to solve practical problems without destruction of the integrity of the object under inspection. The development of scientific nondestructive methods became possible in the early 20th century with the development of the elasticity theory and instrumentation for the measurement of wood properties (Bucur, 1995).

Nondestructive wood evaluation for determining its technological characteristics is an important tool for understanding the variability between individuals and characterization of materials in the field. Nondestructive techniques have been increasingly used for several forestry and industrial sectors. Assessing the wood quality by simpler and faster techniques is a fundamental need in the *Eucalyptus* forests qualification (Gouvêa et al., 2011).

Several researches have been developed in order to predict wood properties by nondestructive methods. Studies presented by Raymond & Muneri (2001), Downes et al. (2002), Jones et al. (2006), Hein et al. (2009a, b, 2010a), Andrade et al. (2010), Hoibo & Vestol (2010), Hein et al. (2010b), Couto et al. (2013), and Downes et al. (2012) are some examples of using nondestructive methods in assessing timber properties.

Currently, there is great demand for fast and reliable methods for selecting and classifying woods, both by geneticists as by mechanical processing industries (Yang & Evans, 2003). Nondestructive methods or tests have great potential as analysis tools, since they are intended to qualify the material without impairing its future use (Couto et al., 2013). Most studies have been conducted using alternative methods for fast and reliable wood characterization that, along with traditional methods, can result both in quality analysis and time gains (Andrade et al., 2010).

Among the several nondestructive methods, resonance or transverse vibration method and near infrared spectroscopy (NIR) stand out.

7.1. Resonance

The resonance method consists in the vibration of a sample timber, obtaining the modulus of elasticity of the material based on the analysis of the main vibration frequencies (Brancheriau & Baillères, 2003). Commonly referred to as "resonance method" in international literature, this technique has stood out among nondestructive tests, especially for strong adhesion between the physical phenomenon of the model and the corresponding theoretical mathematical model (Targa et al., 2005).

According to Hein et al. (2010c), with the use of the resonance technique, it is possible to provide a large and accurate data set of the key mechanical traits (such as Young, shear modulus and loss tangent) of wood even in lumber containing knots, small cracks and slightly damaged areas.

The transverse vibration method has stood out among those used in nondestructive testing, especially for strong adhesion between the physical phenomenon of the model and the corresponding theoretical mathematical model (Calil & Miná, 2003). Vibration analysis is a simple and efficient way of characterizing the elastic properties of a mass (Brancheriau & Baillères, 2003).

According to Nogueira & Ballarin (2008), currently, the resonance method is considered a technique that can provide reliable values for the modulus of elasticity and can be used in any type of timber, with any cross section and also in glued laminated wood or wooden panels. The natural frequency of vibration of the material is correlated with its bending stiffness (Carreira & Candian, 2008).

Resonance methods are usually used with samples, thus, it cannot be used in standing tree evaluations but it can be used in log evaluations. The important dynamic property of any elastic system is the natural vibration frequency. For a vibrating beam of certain dimensions, the natural vibration frequency is mainly related to the modulus of elasticity and density. Thus, the modulus of elasticity of a material can be determined from the measurement of the natural vibration frequency of prismatic bars and the mathematical relationships between both (Malhotra & Sivasundaram, 2004).

According to Candian & Sales (2009), the first transverse vibration test using the technique was performed by a French scientist for determining the modulus of elasticity of an iron bar. Subsequently, these results were compared with results obtained in tensile tests on iron bars, one of the first attempts to compare elastic constant values obtained in dynamic tests with values resulting from static tests.

Several authors have conducted studies using resonance method to determine wood properties, such as Halabe et al. (1997), Haines et al. (1996), Haines & Leban (1997), Ilic (2001), Burdzik & Nkwera (2002), Wang et al. (2002), Shan-qing & Feng (2007), Chauhan et al. (2007), Carreira & Candian (2008), Candian & Sales (2009), Hein et al. (2010c, 2011), Leite et al. (2012), Yang et al. (2015), and others. All these researchers concluded that resonance technique can potentially characterize the mechanical properties of wood in a simple and rapid way and at low cost.

7.2. Near infrared spectroscopy

Near infrared (NIR) spectroscopy has been used for the characterization of different forms of biomass for more than 15 years. Currently, the use of NIR is focused on agricultural and food industries (Marten et al., 1985).

According to Pasquini (2003), NIR is the measurement of the absorption / reflection intensity near infrared light (in the range from 750 to 2500 nm), in relation to the wavelength held by the sample.

NIR spectroscopy analysis is a fast, environment-friendly analytical method that has gained widespread acceptance in recent years. It is based on vibrational spectroscopy that monitors changes in molecular vibrations intimately associated with changes in molecular structure. Spectra within the NIR region consist of overtone and combination bands of fundamental vibrations of functional groups that occur in the middle infrared region, mainly CH, OH and NH, which represent the backbone of all biological compounds. NIR spectroscopy has a substantial edge over other indicators because the spectra contain information about all chemical constituents of organic material (Baillères et al., 2002).

Analytical methods derive from the use of the NIR spectroscopic region and reflect its most significant characteristics, such as: fast (one minute or less per sample), non-destructive, non-invasive, with high penetration of the probing radiation beam, suitable for in-line use, nearly universal application (any molecule containing C-H, NH, S-H or O-H bonds), with minimum sample preparation demands (Williams & Norris, 2001).

According to Pasquini (2003), NIR spectrum originates from radiation energy transferred to mechanical energy associated with the motion of atoms held together by chemical bonds in a molecule. It is possible to understand how NIR works based on the theory that radiation of a given frequency, capable to supply exactly the energy between two vibrational levels or their overtones or combinations of two or more vibrations, can be absorbed by the molecule and produce excitation to a higher vibrational energy level. Since the 1980's, this technique has been used to estimate various wood properties; however, since 1990's, many studies have shown how it works, as showing the Table 3.

Table 3. Studies presenting NIR-based calibrations for wood properties.

Wood property	Specie	Statistical model (R^2/R)	SECV/ RMSECV	Reference
Basic density (g.cm^{-3})	*Larix decidua* Mill.	0.98	0.023	Gindl & Schöberl (2004)
Bending strength (MPa)		0.94	6.619	
Compressive strength (MPa)		0.97	3.227	
MOE (MPa)		0.96	814.8	
MOE (GPa)	*Larix gmelinii* var. *japonica* x *Larix kaempferi*	0.82	1.15	Fujimoto et al. (2008)
MOR (MPa)		0.79	6.39	
Guaiacyl units(%)	*Populus alba* x *Populus tremula*	0.96	0.202	Robinson & Mansfield (2009)
Syringyl units (%)		0.96	0.201	
p- hydroxyphenyl (%)		0.71	0.201	
MOE (MPa)	*Eucalyptus grandis* and *E. urophylla*	0.79	652.2	Hein et al. (2009b)
MOE (MPa)	*Eucalyptus urophylla*	0.78	1680.2	Andrade et al. (2010)
MOR (MPa)		0.75	10.4	
MFA (degrees)	*Eucalyptus urophylla*	0.64	0.84	Hein et al. (2010a)
Klason lignin (%)	*Eucalyptus urophylla*	0.76-0.88	0.44-0.74	Hein et al. (2010b)
Acid soluble lignin (%)		0.74-0.88	0.073-0.099	
S/G ratio by thioacidolysis (%)		0.74-0.94	0.072-0.167	
MOE (MPa)	*Eucalyptus grandi sx E. urophylla* hybrids	0.81	1.149	Hein et al. (2010c)
Lignin (%)	Seven species of pines	0.95	0.44	Hodge & Woodbridge (2010)
Cellulose (%)		0.72	1.10	
MOE (MPa)	*Pinus* spp. Veneers	0.78	841	Carneiro et al. (2010)

R^2: Determination coefficient for calibration set; R: Pearson linear correlation coefficient; SECV: standard error of calibration; RMSECV: root mean square error of cross validation.

8. CONCLUSION

Eucalyptus has been the focus of several studies of genetic breeding due to its rapid growth and good adaptation to climatic and soil conditions of Brazil. However, for each intended use, whether pulp and paper, charcoal production, and others, wood requires specific, sometimes contrasting features. The wood characteristics may present variations in its properties and performance in specific applications, and can be caused by both genetic and environmental factors. However, how genetic and environmental factors act on wood variation along the trunk is still unclear. Another point is that even with new genetic breeding programs, the mechanical properties of wood have not been considered in these programs, since the selection of new material is always based on the growing rate, cellulose and lignin content and wood density.

ACKNOWLEDGEMENTS

The author expresses special thanks to the Wood Science and Technology Laboratory of the Federal University ofLavras (UFLA, Brazil) for supporting the experimental work. This study was funded by CNPq (National Council for Scientific and Technological Development, Brazil), CAPES (Higher Education Personnel Improvement Coordination, Brazil), and FAPEMIG (Foundation for Research Support of the State of Minas Gerais), Brazil.

SUBMISSION STATUS

Received: 13 aug., 2018
Accepted: 13 july, 2019

CORRESPONDENCE TO

Maria Fernanda Vieira Rocha
Departamento de Ciências Florestais,
Universidade Federal de Lavras – UFLA,
Av. Bueno da Fonseca, 543, Inácio Valentim,
CEP 37200-000, Lavras, MG, Brasil
e-mail: mfvrocha@yahoo.com.br

FINANCIAL SUPPORT

CNPq (National Council for Scientific and Technological Development, Brazil), CAPES (Higher Education Personnel Improvement Coordination, Brazil), and FAPEMIG (Foundation for Research Support of the State of Minas Gerais).

REFERENCES

Alcorn PJ, Pyttel P, Bauhus J, Smith RGB, Thomas D, James R et al. Effects of initial planting density on branch development in 4-year-old plantation grown *Eucalyptus pilularis* and *Eucalyptus cloeziana* trees. *Forest Ecology and Management* 2007; 252(1-3): 41-51. http://dx.doi.org/10.1016/j.foreco.2007.06.021.

Andrade CR, Trugilho PF, Napoli A, Vieira RS, Lima JT, Sousa LC. Estimation of the mechanical properties of wood from *Eucalyptus urophylla* using near infrared spectroscopy. *Revista Ceres* 2010; 16(3): 291-298.

Antony F, Schimleck LR, Daniels RF, Clark A 3rd, Borders BE, Kane MB et al. Whole-tree bark and wood properties of Loblolly pine from intensresively managed plantations. *Forest Science* 2015; 61(1): 55-66. http://dx.doi.org/10.5849/forsci.12-030.

Baillères H, Davrieux F, Ham-Pichavant F. Near infrared analysis as a tool for rapid screening of some major wood characterists in a *Eucalyptus* breeding program. *Annals of Forest Science* 2002; 59(5-6): 479-490. http://dx.doi.org/10.1051/forest:2002032.

Balloni EA. Influência do espaçamento de plantio na produtividade florestal. *Silvicultura* 1983; 8(31): 588-592.

Bendtsen BA. Properties of wood from improved and intensively managed trees. *Forest Products Journal* 1978; 28(10), 61-72.

Binkley D, Stape JL, Ryan MG, Barnard H, Fownes J. Age- related decline in forest ecosystem growth: an individual- tree, stand- structure hypothesis. *Ecosystems (New York, N.Y.)* 2002; 5(1): 58-67. http://dx.doi.org/10.1007/s10021-001-0055-7.

Brancheriau L, Baillères H. Use of the partial least squares method with acoustic vibration spectra as a new grading technique for structural timber. *Holzforschung* 2003; 57(6): 644-652. http://dx.doi.org/10.1515/HF.2003.097.

Bucur V. *Acoustics of wood*. Boca Raton: CRC Press, 1995. 284 p.

Burdzik WMG, Nkwera PD. Transverse vibration tests for prediction of stiffness and strength properties of full size *Eucalyptus grandis. Forest Products Journal* 2002; 52: 6.

Calil C Jr, Miná AJS. Vibração transversal: um método eficiente para classificação de peças estruturais de madeira. *Revista Brasileira de Engenharia Agrícola e Ambiental* 2003; 7(2): 335-338. http://dx.doi.org/10.1590/S1415-43662003000200025.

Candian M, Sales A. Aplicação das técnicas não-destrutivas de ultrassom, vibração transversal e ondas de tensão para avaliação de madeira. *Revista Ambiente Construído* 2009; 9(4): 83-98.

Carneiro ME, Magalhães WLE, Muñiz GIB, Schimleck LR. Near infrared spectroscopy and chemometrics for predicting specific gravity and flexural modulus of elasticity of *Pinus* spp. veneers. *Journal of Near Infrared Spectroscopy* 2010; 18(6): 481-489. http://dx.doi.org/10.1255/jnirs.911.

Carreira MR, Candian M. Teste de um equipamento para classificação de peças estruturais de madeira pela técnica da vibração transversal. *Revista Ciências Exatas e da Terra* 2008; 29(1), 3-14.

Chafe SC. Growth stress in trees. *Australian Forest Research* 1979; 9(3): 203-223.

Chauhan SS, Entwistle KM, Walker CF. Search for a relationship between stress wave velocity and internal stresses in eucalypts and radiata pine. *Holzforschung* 2007; 61(1): 60-64. http://dx.doi.org/10.1515/HF.2007.010.

Chen S, Arnold R, Li Z, Li T, Zhou G, Wu Z et al. Tree and stand growth for clonal *E. urophylla x grandis* across a range of initial stockings in southern China. *New Forests* 2011; 41(1): 95-112. http://dx.doi.org/10.1007/s11056-010-9213-0.

Clark A III, Saucier JR. Influence of plant density, intensive culture, geographic location, and species on juvenile wood formation in Southern Pine. *Georgia Forest Research Paper*, 1991; 85: 1-13.

Cockerham ST. Irrigation and planting density affect river red gum growth. *California Agriculture* 2004; 58(1): 40-43. http://dx.doi.org/10.3733/ca.v058n01p40.

Couto AM, Trugilho PF, Neves TA, Protásio TP, Sá VA. Modeling of basic density of wood from *Eucalyptus grandis* and *Eucalyptus urophylla* using nondesctructive methods. *Revista Ceres* 2013; 19(1): 27-34.

Dias AF Jr, Santos PV, Pace JHC, Carvalho AM, Latorraca JV. Caracterização da madeira de quatro espécies florestais para uso em movelaria. *Revista Ciência da Madeira* 2013; 4(1): 93-107. http://dx.doi.org/10.12953/2177-6830.v04n01a08.

Donaldson L. Microfibril angle: measurement, variation and relationships – a review. *IAWA Journal* 2008; 29(4): 345-386. http://dx.doi.org/10.1163/22941932-90000192.

Downes G, Evans R, Wimmer R, French J, Farrington A, Lock P. Wood, pulp and handsheet relationships in plantation grown *Eucalyptus globulus*. *Appita Journal* 2003; 56: 221-228.

Downes G, Worledge D, Schimleck L, Harwood C, French J, Beadle C. The effect of growth rate and irrigation on the basic density and kraft pulp yield of *Eucalyptus globulus* and *E. nitens*. *New Zealand Journal of Forestry Science* 2006; 51: 13-22.

Downes GM, Drew D, Battaglia M, Schulze D. Measuring and modelling stem growth and wood formation: an overview. *Dendrochronologia* 2009; 27(2): 147-157. http://dx.doi.org/10.1016/j.dendro.2009.06.006.

Downes GM, Harwood CE, Wiedemann J, Ebdon N, Bond H, Meder R. Radial variation in kraft pulp yield and celulose content in *Eucalyptus globulus* wood across three contrasting sites predicted by near infrared spectroscopy. *Canadian Journal of Forest Research* 2012; 42(8): 1577-1586. http://dx.doi.org/10.1139/x2012-083.

Downes GM, Nyakeuengama JG, Evans R, Northway R, Blakemore P, Dickson RL et al. Relationship between wood density, microfibril angle and stiffness in thinned and fertilized *Pinus radiata*. *IAWA Journal* 2002; 23(3): 253-265. http://dx.doi.org/10.1163/22941932-90000302.

Downes GM, Raymond CA. Appendix 1: wood density variation in plantation eucalypts. In: Downes GM, Hudson IL, Raymond CA, Dean GH, Michell AJ, Schimleck LR et al. *Sampling plantation eucalypts for wood and fiber properties*. Melbourne: CSIRO Publishing; 1997. p. 88-98. http://dx.doi.org/10.1071/9780643105287.

Downes GM, Touza M, Harwood C, Vietheer MW. NIR detection of non-recoverable colapse in sawn boards of *Eucalyptus globulus*. *European Journal of Wood and Wood Products* 2014; 72(5): 563-570.

Drew DM, Downes GM, Battaglia M. CAMBIUM, a process-based model of daily xylem development in *Eucalyptus*. *Journal of Theoretical Biology* 2010; 264(2): 395-406. http://dx.doi.org/10.1016/j.jtbi.2010.02.013. PMid:20167220.

Evans JW, Senft JF, Green DW. Juvenile wood effect in red alder: analysis of physical and mechanical data to delineate juvenile and mature wood zones. *Forest Products Journal* 2000a; 50(7-8): 75-87.

Evans R, Stringer S, Kibblewhite RP. Variation of microfibril angle, density and fiber orientation in twenty-nine *Eucalyptus nitens* trees. *Appita Journal* 2000b; 53: 450-457.

Forrester DI, Baker TG. Growth responses to thinning and pruning in *Eucalyptus globulus, Eucalyptus nitens,* and *Eucalyptus grandis* plantations in southeastern Australia. *Canadian Journal of Forest Research* 2012; 42(1): 75-87. http://dx.doi.org/10.1139/x11-146.

Forrester DI, Medhurst JL, Wood M, Beadle CL, Valencia JC, Harwood C. *The effect of solid-wood silviculture on growth, form and wood properties in Eucalyptus plantations: an Australian perspective*. Melbourne: Forest & Wood Products Australia; 2013. 99 p.

French J, Conn AB, Batchelor WJ, Parker IH. The effect of fiber fibril angle on some handsheet mechanical properties. *Appita Journal* 2000; 53(3): 210-226.

Fujimoto T, Yamamoto H, Tsuchikawa S. Estimation of wood stiffness and strength properties of hybrid larch by near infrared spectroscopy. *Applied Spectroscopy* 2008; 61(8): 882-888. http://dx.doi.org/10.1366/000370207781540150. PMid:17716408.

Garcia CH, Corradine L, Alvarenga SF. *Comportamento florestal do Eucalyptus grandis e Eucalyptus saligna em diferentes espaçamentos.* Piracicaba: IPEF; 1991. 8 p.

Gindl W, Schöberl T. The significance of the elastic modulus of wood cell walls obtained from nanoindentation measurements. *Composites Part A* 2004; 35: 1345-1349.

Gouvêa AFG, Trugilho PF, Gomide JL, Silva JRM, Andrade CR, Alves ICN. Determinação da densidade básica da madeiras de Eucalyptus por diferentes métodos não destrutivos. *Revista Árvore* 2011; 35(2): 349-358.

Haines DW, Leban J-M, Herbé C. Determination of Young's modulus for spruce, fir and isotropic materials by the resonance flexure method with comparisons to static flexure and other dynamic methods. *Wood Science and Technology* 1996; 30: 253-263. http://dx.doi.org/10.1007/BF00229348.

Haines DW, Leban JM. Evaluation of the MOE of Norway spruce by the resonance flexure method. *Forest Products Journal* 1997; 47: 10.

Halabe UB, Bidigalu GM, Gangarao HVS, Ross RJ. Nondestructive evaluation of green wood using stress wave and transverse vibration techniques. *Materials Evaluation* 1997; 55(9): 1013-1018.

Hapla F, Oliver-Villanueva JV, González-Molina JM. Effect of silvicultural management on wood quality and timber utilisation of *Cedrus atlântica* in the European mediterranean área. *Holz als Roh- und Werkstoff* 2000; 58(1-2): 1-8. http://dx.doi.org/10.1007/s001070050377.

Harrington TB, Harrington CA, Debell DS. Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). *Forest Ecology and Management* 2009; 258(1): 18-25. http://dx.doi.org/10.1016/j.foreco.2009.03.039.

Hart JF. *A review of the effects of silviculture on wood quality*. Columbia: The University of British Columbia; 2010. Wood 493. 27 p.

Hein PRG, Lima JT, Chaix G. Robustness of models based on near infrared spectra to predict the basic density in *Eucalyptus urophylla* wood. *Journal of Near Infrared Spectroscopy* 2009a; 17(3): 141-150. http://dx.doi.org/10.1255/jnirs.833.

Hein PRG, Campos ACM, Lima JT, Trugilho PF, Chaix G. Estimativa da resistência e da elasticidade à compressão paralela às fibras da madeira de *Eucalyptus grandis* e *E. urophylla* usando a espectroscopia no infravermelho próximo. *Scientia Forestalis* 2009b; 37(82): 119-129.

Hein PRG, Brancheriau L, Lima JT, Rosado AM, Gril J, Chaix G. Clonal and environmental variation of structural timbres of *Eucalyptus* for growth, density and dynamic properties. *Revista Ceres* 2010a; 16: 74-81.

Hein PRG, Lima JT, Chaix G. Effects of sample preparation on NIR spectroscopic estimation of chemical properties of *Eucalyptus urophylla* S. T. Blake wood. *Holzforschung* 2010b; 64: 45-54.

Hein PRG, Brancheriau L, Trugilho PF, Lima JT, Chaix G. Resonance and near infrared spectroscopy for evaluating dynamic wood properties. *Journal of Near Infrared Spectroscopy* 2010c; 18(6): 1-12. http://dx.doi.org/10.1255/jnirs.907.

Hein PRG, Lima JT, Gril J, Rosado AM, Brancheriau L. Resonance of scantlings indicates the stiffness even of small specimens of *Eucalyptus* from plantations. *Wood Science and Technology* 2011; 41: 621-635.

Hein PRG, Chaix G, Clair B, Brancheriau L, Gril J. Spatial variation of wood density, stiffness and microfibril angle along *Eucalyptus* trunks grown under contrasting growth conditions. *Trees (Berlin)* 2016; 30(3): 871-882. http://dx.doi.org/10.1007/s00468-015-1327-8.

Hodge GR, Woodbridge WC. Global near infrared models to predict lignin and cellulose content of pine wood. *Journal of Near Infrared Spectroscopy* 2010; 18(6): 367-380. http://dx.doi.org/10.1255/jnirs.902.

Hoibo O, Vestol GI. Modelling the variation in modulus of elasticity and modulus of rupture of Scots pine round timber. *Canadian Journal of Forest Research* 2010; 40(4): 668-678. http://dx.doi.org/10.1139/X10-021.

Huang C-L, Lindstrom H, Nakada R, Ralston J. Cell wall structure and wood properties determined by acoustics - a selective review. *Holz als Roh- und Werkstoff* 2003; 61(5): 321-335. http://dx.doi.org/10.1007/s00107-003-0398-1.

Husch B, Miller CI, Beers TW. *Forest mensuration*. New York: Ronald Press; 1972. 410 p.

Ilic J. Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis* R. Baker. *Holz als Roh- und Werkstoff* 2001; 59(3): 169-175. http://dx.doi.org/10.1007/s001070100198.

Innes T. Processing and wood properties of four ages of *Eucalyptus obliqua. Holz als Roh- und Werkstoff* 2007; 65(3): 197-200. http://dx.doi.org/10.1007/s00107-006-0138-4.

Inoue MT, Figueiredo A Fo, Lima R. Influência do espaçamento de crescimento na altura e diâmetro de *Pinus taeda* L. *Scientia Forestalis* 2011; 39(91): 377-385.

Ishiguri F, Kasai S, Yokotá S, Iizuka K, Yoshizawa N. Wood quality of Sugi (*Cryptomeria japônica*) grown at four initial spacings. *IAWA Journal* 2005; 26(3): 375-386. http://dx.doi.org/10.1163/22941932-90000122.

Jones PD, Schimleck LR, Peter GF, Daniels RF, Clark A 3rd. Nondestructive estimation of wood chemical composition of sections of radial wood strips by diffuse reflectance near infrared spectroscopy. *Wood Science and Technology* 2006; 40(8): 709-720. http://dx.doi.org/10.1007/s00226-006-0085-6.

Joza LA, Middleton GR. *Wood quality attributes and their practical implications*. Vol. 34. Vancouver: Forintek Canada Corp; 1994. p. 1-42.

Kang K, Zhang SY, Mansfield SD. The effects of initial spacing on wood density, fiber and pulp properties in jack pine (*Pinus banksiana* Lamb.). *Holzforschung* 2005; 58(5): 455-463.

Kollmann FFP, Cotê WA. *Principles of wood science and technology*. Vol. 1. Berlim: Springer-Verlag; 1968. 592 p. http://dx.doi.org/10.1007/978-3-642-87928-9.

Larson PR, Kretschmann DE, Clark A 3rd, Isebrands JG. *Formation and properties of juvenile wood in southern pines: a synopsis*. Madison: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 2001. 42 p. General Technical Report. FPL-GTR-129. http://dx.doi.org/10.2737/FPL-GTR-129.

Larson PR. Auxin gradients and the regulation of cambial activity. In: Kozlowski TT, editors. *Tree growth*. New York: Ronald Press; 1962.

Leite ERS, Hein PRG, Souza TM, Rabelo GF. Estimation of the dynamic elastic properties of wood from *Copaifera langsdorffii* Desf using resonance analysis. *Revista Ceres* 2012; 18(1): 41-47.

Leite HG, Nogueira GS, Moreira AM. Efeito do espaçamento e da idade sobre variáveis de povoamentos de *Pinus taeda* L. *Revista Árvore* 2006; 4(30): 603-612. http://dx.doi.org/10.1590/S0100-67622006000400013.

Leles PSS, Reis GG, Reis MGF, Morais EJ. Relações hídricas e crescimento de árvores de *Eucalyptus camaldulensis* e *Eucalyptus pellita* sob diferentes espaçamentos na região de cerrado. *Revista Árvore* 1998; 22(1): 41-50.

Li Y, Turnblom EC, Briggs DG. Effects of density control and fertilization on growth and yield of young *Douglas-fir* plantations in the Pacific Northwest. *Canadian Journal of Forest Research* 2007; 37(2): 449-461. http://dx.doi.org/10.1139/X06-234.

Lima IL, Garcia R, Longui EL, Florsheim SMB. Dimensões anatômicas da madeira de *Tectona grandis* Linn. em função do espaçamento e da posição radial do tronco. *Scientia Forestalis* 2011; 39(89): 61-68.

Lima JT, Breese MC, Cahalan CM. Genotype-environment interaction in wood basic density of *Eucalyptus* clones. *Wood Science and Technology* 2000; 34(3): 197-206. http://dx.doi.org/10.1007/s002260000041.

Little CHA, Pharis RP. Hormonal control of radial and longitudinal growth in the tree stem. In: Gartner BL, editor. *Plant stems: physiology and functional morphology*. San Diego: Academic Press; 1995. http://dx.doi.org/10.1016/B978-012276460-8/50015-1.

Malan FS, Hoon M. Effect of initial spacing and thinning on some wood properties of *Eucalyptus grandis. South African Forestry Journal* 1992; 163(1): 13-20. http://dx.doi.org/10.1080/00382167.1992.9629362.

Malhotra VM, Sivasundaram V. Resonant frequency methods. In Malhotra VM, Carino NJ, editors. *Handbook on nondestructive testing of concrete*. 2nd ed. Boca Raton: CRC Press; 2004. p. 7.1-7.21.

Malik MFEI, Abdelgadir AY. Effect of growth rate on wood density of *Eucalyptus camaldulensis* wood of Coppice origin grown in White Nile State Sudan. *Journal of Forest Products & Industries* 2015; 4(3): 86-93.

Malimbwi RE, Persson A, Iddi S, Chamshama SAO, Mwihomeke ST. Effects of spacing on yield and some wood properties of *Cupressus lusitânica* at Rongai, Northern Tanzania. *Forestry* 1992; 65(1): 73-82. http://dx.doi.org/10.1093/forestry/65.1.73.

Marten G, Shenk J, Barton F iii. *Near infrared reflectance spectroscopy (NIRS): analysis of forage quality*. Maryland: USDA Agriculture Research Service; 1985. (Handbook; no. 643).

Medhurst J, Downes G, Ottenschlaeger M, Harwood C, Evans R, Beadle C. Intra-specific competition and the radial development of wood density, microfibril angle and modulus of elasticity in plantation-grown *Eucalyptus nitens. Trees (Berlin)* 2012; 26(6): 1771-1780. http://dx.doi.org/10.1007/s00468-012-0746-z.

Megraw RA. *Wood quality factors in loblolly pine. The influence of tree age, position in tree, and cultural practice on wood specific gravity, fiber length and fibril angle*. Atlanta: TAPPI Press, Technology Park; 1985.

Moore JR, Cown DJ, McKinley RB. Effects of stand density and seedlot on three wood properties of young radiate pine grown at a dry-land site in New Zealand. *New Zealand Journal of Forestry Science* 2015; 45(4): 1-15.

Moulin JC, Arantes MDC, Vidaurre GB, Paes JB, Carneiro ACO. Efeito do espaçamento, da idade e da irrigação nos componentes químicos da madeira de eucalipto. *Revista Árvore* 2015; 39(1): 199-208. http://dx.doi.org/10.1590/0100-67622015000100019.

Naji HR, Bakar ES, Soltani M, Ebadi SE, Abdul-Hamid H, Javad SKS et al. Effect of Initial planting density and tree features on growth, wood density, and anatomical properties from *Hevea brasiliensis. Trial Plantation* 2014; 64(1-2): 41-47.

Neilsen WA, Gerrand AM. Growth and branching habit of *Eucalyptus nitens* at different spacing and the effect of final crop selection. *Forest Ecology and Management* 1999; 123(2-3): 217-229. http://dx.doi.org/10.1016/S0378-1127(99)00044-4.

Nicholson JE, Hillis WE, Ditchburne N. Some tree growth–wood property relationships of eucalypts. *Canadian Journal of Forest Research* 1975; 5(3): 424-432. http://dx.doi.org/10.1139/x75-059.

Nogueira M, Ballarin AW. Efeito da idade na qualificação mecânica da madeira serrada de *Eucalyptus* sp. com uso de ensaios não-destrutivos. *Revista Energia na Agricultura* 2008; 23(3): 74-94.

Oliveira JTS, Silva JC. Variação radial da retratibilidade e densidade básica da madeira de *Eucalyptus saligna* Sm. *Revista Árvore* 2003; 27(3): 381-385. http://dx.doi.org/10.1590/S0100-67622003000300015.

Oliveira SN No, Reis GG, Reis MDGF, Leite HG, Neves JCL. Crescimento e distribuição diamétrica de *Eucalyptus camaldulensis* em diferentes espaçamentos e níveis de adubação na região de Cerrado de Minas Gerais. *Floresta* 2010; 40(4): 755-762.

Panshin AJ, De Zeeuw C. *Textbook of wood technology*. 4th ed. New York: Mc Graw Hill; 1980. 722 p.

Pasquini C. Near infrared spectroscopy: fundamentals, practical aspects and analytical applications. *Journal of the Brazilian Chemical Society* 2003; 14(2): 198-219. http://dx.doi.org/10.1590/S0103-50532003000200006.

Passialis C, Kiriazakos A. Juvenile and mature wood properties of naturally-grown fir trees. *Holz als Roh- und Werkstoff* 2004; 62(6): 476-478. http://dx.doi.org/10.1007/s00107-004-0525-7.

Paul BH. *The application of silviculture in controlling the specific gravity of wood*. Washington: USDA Forest Service; 1963. (Technical Bulletin; no. 1288).

Pereira BLC, Oliveira AC, Carvalho AML, Carneiro ACO, Santos LC, Vital BR. Quality of wood and charcoal from *Eucalyptus* clones for ironmaster use. *Journal of Forestry Research* 2012; 2012: 1-8. http://dx.doi.org/10.1155/2012/523025.

Pliura A, Yu Q, Zhang SY, Mackay J, Perinet P, Bousquet J. Variation in wood density and shrinkage and their relationship to growth of selected young poplar hybrid crosses. *Forest Science* 2005; 51(5): 472-482.

Raymond CA, Muneri A. Nondestructive sampling of *Eucalyptus globulus* and *E. nitens* for wood properties.I. Basic density. *Wood Science and Technology* 2001; 35(1-6): 27-39. http://dx.doi.org/10.1007/s002260000078.

Raymond CA, Schimleck LR, Muneri A, Michell AJ. Non destructive sampling of *Eucalyptus globulus* and *E. nitens* for wood properties. III. Predicted pulp yield using near infrared reflectance analysis. *Wood Science and Technology* 2001; 35(3): 203-215. http://dx.doi.org/10.1007/s002260100092.

Raymond CA. Genetics of *Eucalyptus* wood properties. *Annals of Forest Science* 2002; 59(5-6): 525-531. http://dx.doi.org/10.1051/forest:2002037.

Robinson AR, Mansfield SD. Rapid analysis of poplar lignin monomer composition by a revised thioacidolysis procedure and NIR-based prediction modeling. *The Plant Journal* 2009; 58(4): 706-714. http://dx.doi.org/10.1111/j.1365-313X.2009.03808.x. PMid:19175772.

Rocha MFV, Vital BR, Carneiro ACO, Carvalho AMML, Cardoso MT, Hein PRG. Effects of plant spacing on the physical, chemical and energy properties of *Eucalyptus* wood and bark. *Journal of Tropical Forest Science* 2016; 28(3): 243-248.

Ross RJ, Pellerin RF. *Nondestructive testing for assessing wood members in structures: a review*. Madison: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1994. 40 p. General Technical Report. FPL-GTR-70. http://dx.doi.org/10.2737/FPL-GTR-70.

Sanquetta CR, Mora AL, Borsato R, Vidal MAS, Peixoto AM, Chiaranda R. Efeito do espaçamento de plantio em reflorestamentos - II. *Pinus taeda* L. em Jaguariaíva, PR. *Revista Acadêmica: Ciências Agrárias e Ambientais* 2003; 1(1): 55-61. http://dx.doi.org/10.7213/cienciaanimal.v1i1.14889.

Santos RCD, Carneiro ADCO, Castro AFM, Castro RVO, Bianche JJ, Souza MM et al. Correlation of quality parameters of wood and charcoal of clones of *Eucalyptus. Scientia Forestalis* 2011; 39(90): 221-230.

Savidge RA. Tree growth and wood quality. In: Barnett JR, Jeronimidis G, editors. *Wood quality and its biological basis*. New York: CRC Press, Blackwell Publishing; 2003. p. 1-29.

Savidge RA. Xylogenesis, genetic and environmental regulation - a review. *IAWA Journal* 1996; 17(3): 269-310.

Serpa PN, Vital BR, Lucia MD, Pimenta AS. Avaliação de algumas propriedades da madeira de *Eucalyptus grandis, Eucalyptus saligna* e *Pinus elliottii. Revista Árvore* 2003; 27(5): 723-733. http://dx.doi.org/10.1590/S0100-67622003000500015.

Shan-qing L, Feng F. Comparative study on three dynamic modulus of elasticity and static modulus of elasticity for Lodgepole pine lumber. *Journal of Forestry Research* 2007; 18(4): 309-312. http://dx.doi.org/10.1007/s11676-007-0062-4.

Souza GM, Tiné MAS, Buckeridge MS. Ajustando os botões: como as plantas lidam com o aumento do CO2 atmosférico? In: Buckeridge MS, editor. *Biologia & mudanças climáticas no Brasil*. São Paulo: Rima; 2008. cap. 6, p. 101-113.

Stape JL, Binkley D. Insights from full-rotation Nelder spacing trials with *Eucalyptus* in São Paulo, Brazil. *South Forests* 2010; 72(2): 90-97.

Sundberg B, Uggla C, Tuominen H. Cambial growth and auxin gradients. In: Savidge R, Barnett JR, Napier R, editors. *Cell and molecular biology of wood formation*. Oxford: Bios Scientific Publishers Ltd; 2000. 169 p.

Targa LA, Ballarin AW, Biaggioni MAM. Avaliação do módulo de elasticidade da madeira com uso de método não-destrutivo de vibração transversal. *Revista Engenharia Agrícola* 2005; 25(2): 291-299. http://dx.doi.org/10.1590/S0100-69162005000200001.

Taylor FW. Variation in the anatomical properties of South African grown *Eucalyptus grandis. Appita* 2010; 27(3): 171-184.

Tong QJ, Fleming RL, Tanguay F, Zhang SY. Wood and lumber properties from unthinned and precommercially thinned black spruce plantations. *Wood and Fiber Science* 2009; 41(2): 168-179.

Trugilho PF, Bianchi ML, Rosado SC, Lima JT. Qualidade da madeira de clones de espécies e híbridos naturais de *Eucalyptus. Scientia Forestalis* 2007;(73): 55-62.

Wang X, Ross RJ, Mattson JA, Erickson JR, Forsman JW, Geske EA et al. Nondestructive evaluation techniques for assessing modulus of elasticity and stiffness of small-diameter logs. *Forest Products Journal* 2002; 52: 2.

Watson P, Garner C, Robertson R, Reath S, Gee W, Hunt K. The effects of initial tree spacing on the fiber properties of plantation-grown coastal western hemlock. *Canadian Journal of Forest Research* 2003; 33(12): 2460-2468. http://dx.doi.org/10.1139/x03-171.

Wentzel-Vietheer M, Washusen R, Downes GM, Harwood C, Ebdon N, Ozarska B et al. Prediction of nonrecoverable collapse in *Eucalyptus globulus* from near infrared scanning of radial wood samples. *European Journal of Wood and Wood Products* 2013; 71(6): 755-768. http://dx.doi.org/10.1007/s00107-013-0735-y.

Williams P, Norris K, editors. *Near-infrared technology in the agricultural and food industrial*. 2nd ed. St. Paul: American Association of Cereal Chemistry, Inc.; 2001.

Yang BZ, Seale RD, Shmulsky R, Dahlen J, Wang X. Comparison of nondestructive testing methods for evaluating NO.2 Southern Pine lumber: part A, modulus of elasticity. *Wood and Fiber Science* 2015; 47(4): 375-384.

Yang JL, Evans R. Prediction of MOE of eucalypt wood from microfibril angle and density. *Holz als Roh- und Werkstoff* 2003; 61(6): 449-452. http://dx.doi.org/10.1007/s00107-003-0424-3.

Yang KC, Hazenberg G. Impact of spacing on tracheid lenght, relative density, and growth rate of juvenile wood and mature wood in *Picea mariana*. *Canadian Journal of Forest Research* 1994; 24(5): 996-1007. http://dx.doi.org/10.1139/x94-130.

Zobel B, Van Buijtenen B. *Wood variation: its causes and control*. New York: Springer; 1989. 363 p. http://dx.doi.org/10.1007/978-3-642-74069-5.

Zobel B. Silvicultural effects on wood properties. *IPEF International* 1992; 2: 31-38.

Zobel B. Wood quality from fast-grown plantations. *Tappi Journal* 1981; 64(1)

Zobel BJ, Jett JB. *Genetics of wood production*. Berlin: Springer; 1995. 337 p. http://dx.doi.org/10.1007/978-3-642-79514-5.