UNIVERSIDADE FEDERAL DE LAVRAS

MARIA FERNANDA VIEIRA ROCHA

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LAVRAS – MG
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Coorientadora
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Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Rocha, Maria Fernanda Vieira.
Influence of plant spacing and genetic material on wood density and stiffness in *Eucalyptus* stands / Maria Fernanda Vieira Rocha. - 2017.
97 p. : il.

Orientador(a): Paulo Ricardo Gherardi Hein.
Coorientador(a): Ana Márcia Macedo Ladeira Carvalho.
Tese (doutorado) - Universidade Federal de Lavras, 2017.
Bibliografia.

1. Wood quality. 2. NIR spectroscopy. 3. Plant spacing. I. Hein, Paulo Ricardo Gherardi. II. Carvalho, Ana Márcia Macedo Ladeira. III. Título.

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INFLUÊNCIA DO ESPAÇAMENTO DE PLANTIO E MATERIAL GENÉTICO NA DENSIDADE E RIGIDEZ DA MADEIRA EM PLANTIOS DE *Eucalyptus*

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APROVADA em 08 de dezembro de 2017.

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2017

À minha mãe Edileuza por todo apoio
e por ser o meu maior exemplo de vida.
Dedico

AGRADECIMENTOS

Agradeço primeiramente a Deus, pela oportunidade de concretizar mais um sonho.

À minha família, minha mãe Edileuza, meu pai Damázio, e às minhas irmãs Alessandra, Amanda e Mariana, por todo apoio, incentivo, e por acreditarem tanto em mim.

Aos meus parentes e amigos, o meu muito obrigada.

À Universidade Federal de Lavras, especialmente ao Departamento de Ciência e Tecnologia da Madeira, pela oportunidade.

À CAPES, pela concessão da bolsa de doutorado. À FAPEMIG e ao CNPq.

À empresa TTG Brasil Investimentos Florestais, ao Nairam Félix, Marcos, Renato e demais funcionários, pelo material cedido e toda contribuição e apoio no desenvolvimento desta tese de Doutorado.

A meu amigo Alberto Barbosa por todo carinho e atenção.

Ao professor Paulo Ricardo Gherardi Hein, por toda ajuda e pela orientação.

À professora Ana Márcia pela co-orientação, conselhos e amizade.

Aos professores José Reinaldo, Paulo Trugilho e José Tarcísio, por toda amizade, ensinamentos compartilhados, conselhos e momentos de descontração.

Aos professores Gustavo Tonoli e Saulo Rocha, por toda ajuda e amizade.

Ao meu amigo Renato Castro por todo incentivo, amizade e boa vontade em me ajudar.

A todos funcionários da UFLA, em especial à Chica, Raísa, Claret, Carlos e Heber, por toda ajuda durante esses anos.

Ao EBW+ e à Universidade de Uppsala pela oportunidade de realizar parte do meu doutorado na Suécia.

Às minhas queridas amigas, Roseli, Tânia, Cleonice, Mirian, Léia, por alegrarem os meus dias na UFLA.

Aos meus colegas da sala de estudos, Taís, Ana Clara, Jeimy, Arlila, Katyanne, Márcia, Bruno, Élder, Matheus e Luana, por compartilhar dos meus dias durante o doutorado e por serem não só colegas, mas amigos que levarei para a vida toda.

Aos meus amigos Cilene, Lisiane, Thatyane, Áureo, Claudinéia, Isabel, Luciano, Pâmela, Anna Carolina, Thais, Thawane, Lívia, Poliana, Michele, Carolina e Naiara, por toda amizade e pelo carinho que sempre tiveram comigo.

A todos os colegas da pós-graduação em Ciência e Tecnologia da Madeira.

Aos meus amigos da UFV, em especial à Larissa, Déborah, Juliana, Fabiana, Amélia, Antônio, Arthur, Bárbara e Aylson.

À Emylle, Evelize, Raphaela e Leon por toda ajuda no desenvolvimento da minha tese de doutorado.

À Taís por ser a minha grande amiga e por estar sempre do meu lado. Não tenho palavras para te agradecer imensamente por tudo.

MUITO OBRIGADA!

ABSTRACT

Plant spacing between the trees is a major factor in determining tree growth and wood quality, once the productivity of most forest plantations is defined by the supply or capture of sunlight, water and nutrients. Although the effect of low planting density in the variation of tree and wood characteristics has been already reported, the effect of intensive initial densities in plantations has not been fully assessed yet. Thus, the aim of this study was to better understand the effect of initial plant spacing and genetic material on the spatial variation of basic density and stiffness of the wood from 12-years-old *Eucalyptus* clones. The sample of this study consisted of 36 trees, 4 *Eucalyptus* clones planted in three different plant spacing (3 m x 3 m; 3 m x 4 m and 3 m x 8 m). For the basic density of the wood, six discs were cut along the trunk of each tree, being at the base (0), diameter at breast height (BH, at ~1.3 meters), 25, 50, 75, 100% of the commercial tree height. For the stiffness, one log from each tree was used. Near infrared (NIR) calibrations was developed for basic density and stiffness and were used to predict that properties in all samples. The NIRS technique associated with PLS-R was able to predict the basic density and stiffness, with coefficients of determination in the cross-validation (R^2_{cv}) of 0.72 and 0.70, and in the prediction (R^2_p) of 0.73 and 0.79 respectively. The higher the plant spacing between the trees (3 x 8 m), the greater the magnitude of radial variation. The smaller variation was found in the plant spacing 3 x 4 meters. The radial increase in the basic density in the 0 and 50% heights of trees planted at 3 x 4 m was significantly lower than those planted at 3 x 8 m. The results showed that there was an effect of the plant spacing on the radial variation of wood density at heights 0 and 50%. In relation to the effect of the genetic material, it was observed that only at 25% height the values of basic density were statistically different, with the highest values observed in clone i144 lower values in clone i182. For the stiffness, the values had the same behavior of the basic density, however, there was no effect of the genetic material and plant spacing.

Keywords*:* Wood quality. Density. Modulus of elasticity. NIR spectroscopy. Plant spacing. Environmental control. PLS-R.

RESUMO

O espaçamento de plantio entre as árvores é um fator importante na determinação do crescimento da árvore e da qualidade da madeira, uma vez que a produtividade da maioria das plantações florestais é definida pelo fornecimento ou captura da luz solar, água e nutrientes. Embora o efeito da baixa densidade de plantio na variação das características da árvore e da madeira já tenha sido relatado, o efeito das densidades iniciais intensas nas plantações ainda não foi totalmente avaliado. Assim, o objetivo deste estudo foi compreender melhor o efeito do espaçamento inicial de plantio e do material genético na variação espacial da densidade básica e rigidez da madeira de clones de *Eucalyptus* aos 12 anos. A amostragem deste estudo consistiu em 36 árvores, 4 clones de *Eucalyptus* plantados em três diferentes espaçamentos de plantio (3 m x 3 m, 3 m x 4 m e 3 m x 8 m). Para a densidade básica da madeira, seis discos foram retirados ao longo do tronco de cada árvore, sendo na base (0), diâmetro na altura do peito (DAP, a 1,3 metros), 25, 50, 75, 100% da altura comercial da árvore. Para a rigidez, um torete de cada árvore foi usado. As calibrações dos modelos no infravermelho próximo (NIR) foram desenvolvidas para densidade básica e rigidez e foram usadas para predizer essas propriedades em todas as amostras. A técnica NIRS associada ao PLS-R foi capaz de predizer a densidade e a rigidez, com coeficientes de determinação na validação cruzada (R^2cv) de 0,72 e 0,70, e na predição (R^2p) de 0,73 e 0,79, respectivamente. Quanto maior o espaçamento de plantio entre as árvores (3 x 8 m), maior a magnitude da variação radial. A menor variação foi encontrada no espaçamento de plantio de 3 x 4 metros. O aumento radial na densidade básica nas alturas de 0 e 50% de árvores plantadas a 3 x 4 m foi significativamente menor do que aquelas plantadas a 3 x 8 m. Os resultados mostraram que houve efeito do espaçamento da plantio na variação radial da densidade da madeira nas alturas 0 e 50%. Em relação ao efeito do material genético, observou-se que apenas a 25% de altura os valores da densidade básica foram estatisticamente diferentes, com os maiores valores observados no clone i144 e os menores valores no clone i182. Para a rigidez, os valores apresentaram o mesmo comportamento da densidade básica, no entanto, não houve efeito do material genético e do espaçamento de plantio.

Palavras-chave*:* Qualidade da Madeira. Densidade. Módulo de elasticidade. Espectroscopia NIR. Espaçamento de plantio. Controle ambiental. PLS-R.

SUMÁRIO

1 INTRODUCTION

Wood plays a very important role in the world because it can be 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 sawnwood industry, is the key to reducing deforestation of natural forests. The forest sector has played a major role as a source of income for the national economy, generating these products, which are both for direct consumption and export.

The *Eucalyptus* has been the focus of several studies of genetic breeding due to its rapid growth and good adaptation to climatic and soil conditions in Brazil. However, for each intended use, whether pulp and paper, charcoal production, and others, the wood requires specific, sometimes contrasting features. The characteristics of the wood may cause variations in their properties and performance in specific applications, 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 those programs, since the selection of new material is always based on the growing rate, cellulose and lignin content and wood density.

Currently there is no information about how the growing conditions influence the spatial variation of the wood along the stem, since most studies have analyzed the radial or longitudinal variation in just one environment. Thus, it is necessary to generate a better understanding to what extent the plant spacing influences the spatial variation of wood properties in *Eucalyptus* plantations, providing new accurate and reliable information on this issue, that remains still unclear.

Therefore, the main purpose of this study was to determine the effect of plant spacing on spatial variation of wood basic density and stiffness along *Eucalyptus* stems, and understand their effect on the spatial variation. The specific objective was to determine in what extent the plant spacing affects the variation of wood properties.

This study aims to confirm the hypotheses following: (i) the wood properties of elite clones were affected more by environmental factors than by genetic factors. The current genetic materials have lower genetic variability because these generations are the result of many crosses between the most suitable materials; (ii) the plant spacing between trees affects the magnitude of the spatial variation of wood. Trees grown in wider plant spacing produce wood with greater pith to bark variation; (iii) trees growing under widely plant spacing tend to grow more in diameter and produce higher variation on the basic density and MOE of the wood.

2 BACKGROUND

2.1 FOREST PRODUCTIVITY

The forest activity in Brazil has significant economic and social importance, providing a wide range of products that contribute directly and indirectly to generate more than two million jobs, playing key role in the quality of life of the general population (IBÁ, 2017).

After the period in which predominates in the extractive exploitation of native forests in the mid-twentieth century, has begun the research aimed forestry. This aimed to timber production to meet demand, due to the devastation of vegetation to delayed replacement based on native species. So the new forestry was based on exotic species, especially the *Eucalyptus* (FERREIRA; SANTOS, 1997). Due to the growing demand for wood, techniques such as genetic transformation were used to obtain genotypes with high productivity and quality (DIOUF, 2003).

In *Eucalyptus*, a very promising improvement focusing on tree growth was achieved. However, many companies involved in large-scale productions of *Eucalyptus* need other factors to be included that can reduce specific wood consumption or industrial processing cost such as wood basic density, bark percentage, modulus of elasticity, and some other characteristics (WU et al., 2004). Raymond (2002) has pointed out that the degree of genetic control of wood properties is compared to tree growth traits and a series of issues and she presents and discusses a series of challenges for the future in *Eucalyptus* breeding programs.

The high increase in economic value and the stringency of hardwoods have boosted the diversified use of *Eucalyptus* (SOUZA et al., 2012). The productivity of plantations in Brazilian territory is superior to that of traditional countries such as Australia (center of the species origin), and its current situation provides opportunities for the consolidation of Brazil as one of the biggest powers in the world's forest-based industry. The forest sector in Brazil today contributes about 1.1% of the country's Gross Domestic Product (GDP), 6.2% of the Industrial GDP and generates around 3.7 million direct and indirect jobs (IBÁ, 2017).

The country has a planted area of approximately 7.84 million hectares of forests composed mainly of *Eucalyptus* and *Pinus*, with 72.32% of the area planted with *Eucalyptus* (IBA, 2017). The use of *Eucalyptus* and frequent studies on genus in commercial plantations in Brazil occurred at the expense of technological advances, planting techniques and changes in forestry that allowed increasing growth rates and the volume of trees (LIMA et al., 2005).

2.2 INDUSTRIAL IMPORTANCE OF *Eucalyptus* WOOD

Considering the wide variety of species and clones of *Eucalyptus* 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 production of pulp and paper, low wood density combined with long fibers results in collapsible, easy bonding fibers that exhibit low porosity and high strength. Conversely, structural lumber manufacturing requires wood with high density, small knots, and straight grain characteristics to ensure a high quality product (JOZA; MIDDLETON, 1994).

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

Radial and longitudinal variation in wood properties observed along the trunk should be primarily due to differences in the proportion of juvenile and mature wood, the growth layer as well as by wood chemical change (MALAN; HOON, 2010).

Charcoal quality and its production depends, among other factors, on the quality of wood used, which is defined by a set of chemical, physical, mechanical, and anatomical properties, usually interdependent. Nevertheless, regarding the variations that occur in the wood quality of the above cited genus, it is necessary to study it, for this fact may bring about negative consequences in both the quality and yield of charcoal, which will negatively reflect on the operations of the iron and steel industries blast furnaces (SANTOS et al., 2012).

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

In regard to pulp and paper production, Queiroz et al. (2004) emphasized the importance of wood basic density as the main characteristic influencing not only wood cost and industrial yield but, above all, final pulp and paper quality.

Paper strength also depends on the lignin and cellulose content of plant materials; pulp mechanical strength and especially tensile strength is directly proportional to cellulose content, as the lignin is an undesirable macromolecule and its removal during pulping requires high amounts of energy and chemicals (MADAKADZE et al., 1999).

Considering the use of *Eucalyptus* as lumber, Zobel (1981) stated that one of the major problems is related to the existence of growing tensions present, and the highest prevalence occurs in juvenile wood. The growth stress forces are internally generated in the growing tree (KUBLER, 1987), it may cause wood defects such as cracks, warping and reduction in the strength of wood (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, should be taken into account the density, volumetric shrinkage, bend strength, modulus of rupture, compressive strength, tensile strength, shear strength, stiffness, and other wood properties (SERPA et al., 2003).

The Brazilian consumption of hardwood trees planted for industrial use, in 2016, was 206 million cubic meters (m^3), which represents an increase of 6.1% compared to the consumption in 2015 (IBÁ, 2017). Different species of *Eucalyptus* are suitable for many different uses, and its widely used wood as a raw material, for example in the pulp and paper, wood panels, sawnwood and others solid products, charcoal, roundwood, treated wood, wood chips and others, as showed in Table 1.

TABLE 1 - Brazilian Consume of *In Natura* wood for industrial use by tracking and gender, 2016

Segment	**Wood consumption *in natura* (1.000 m^3)**			
	Eucalyptus	***Pinus***	**Others**	**Total**
1. Pulp and Paper	70.74 (45.95%)	9.25 (19.60%)	0.09 (1.76%)	**80.07**
2. Wood panels	5.93 (3.85%)	6.70 (14.20%)	0.37 (7.22%)	**12.99**
3. Sawnwood and others solid products	5.86 (3.81%)	27.37 (58.00%)	0.35 (6.84%)	**33.58**
3. Charcoal	21.46 (13.94%)	-	-	**21.46**
4. Roundwood	46.94 (30.48%)	3.72 (7.88%)	4.31(84.18%)	**54.98**
4. Treated Wood	1.46 (0.95%)	-	-	**1.46**
5. Wood chips and others	1.57 (1.02%)	0.15 (0.32%)	-	**1.71**
TOTAL	**153.96**	**47.19**	**5.12**	**206.25**

Source: IBÁ (2017)

Pulp and paper industry is the main consumer of industrial sector using forest base around 45.95% of the total production of logs of *Eucalyptus* plantations currently in Brazil. Just over 30.48% of the total production of roundwood is consumed as firewood, like in the energy sector, particularly pig iron and steel industries, in turn, uses approximately 13.94% of the wood produced in of charcoal form. A small portion of all timber produced is intended for the production of wood panels (3.85%), and sawnwood and others solid products (3.81%), treated wood (0.95%) and wood chips and others (1.02%). Moreover, 58% of the obtained timber production plantations *Pinus* are intended for sawnwood and other solids products and 14.20% for wood panels.

These values show that the use of *Eucalyptus* as raw material for the production of wood panels, furniture, flooring, construction, among others, still represents a small part of total production in the sector, attributing its low use at the little knowledge and few studies using the *Eucalyptus* by these sectors compared to the paper, energy and pulp sector.

2.3 EFFECT OF SILVICULTURE AND MANAGEMENT AT WOOD QUALITY

2.3.1 Tree growth

Many silvicultural operations can affect the tree growth, like plant spacing, fertilization, pruning, thinning and others (ZOBEL, 1992).

At closer spacings stand leaf areas and biomass develop more rapidly and the site is “fully occupied” sooner. Early stand growth rates will be faster at closer spacings and the 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 the 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), such that higher concentrations of IAA result in larger cell diameters with thinner cell walls, which is known as earlywood (LARSON, 1962; SUNDBERG et al., 2000).

The competition between trees begins when two or more trees are growing in close proximity and fighting for the same resources. Tree growth will be checked when any one of those resources becomes limiting, for example water or other vital nutrient elements, or light due to mutual shading by the tree crowns. The trees exist often in a state where several vital resources are at, or close to, critical limits which can change from time to time throughout the year depending on weather patterns (SHEPHERD, 1986).

At the tree level, the more intense competition for light, water and nutrients will result in a smaller average tree size, but this competition (e.g. for light) improves stem form and controls crown architecture by restricting branch sizes and accelerating rates of branch shedding, thereby improving wood quality (NEILSEN; GERRAND, 1999, ALCORN et al., 2007, FORRESTER; BAKER, 2012). On the other hand, wider spacing results 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 Mallan and Hoon (1992), the control of plant density, either through initial spacing or thinning or a combination of the two and others factors, are silvicultural practices strongly influencing both tree growth and wood formation. Assuming that water and nutrient availability is similar, the individual trees of widely spaced or thinned stock will grow faster than trees that were planted over smaller plant spacing. According to the same author, rapid early growth, resulting in a large core of juvenile wood, is an important consideration regardless of the species involved.

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

The competition for nutrients causes reduction of the increase in plant biomass, thereby trees planted in large spacings 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 stocking in the form of cellulose (DE SOUZA et al., 2008).

According to Balloni (1983), Cockerham (2004) and Li et al. (2007), the growth in diameter of the tree 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 the trees. When it comes to the height of the tree, Neto et al. (2010) says that the growth is less influenced by the spacing, which may vary according to the quality of the location and age of evaluation.

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

The effect of silviculture and management applied on forest planting can cause influence at the tree growth, as many studies show and some examples are shown in Table 2.

Table 2 - Studies conducted analyzing the effect of different plant spacing on tree growth.

Specie	Major findings	Reference
E. camaldulensis and E. pellita	Higher plant spacing: higher growth in diameter and root biomass of both species	Leles et al. (1998)
E. grandis and *E. saligna*	Higher plant spacing: higher diameter at BH height and higher height in both species Smaller plant spacing: higher volumetric podutividade (m^3 / h) for *E. saligna*	Garcia et al. (1991)
P.taeda L.	Higher plant spacing: higher mean square diameter, higher volume and higher survival tree Smaller plant spacing: higher volume per ha	Leite et al. (2006)
P. taeda L.	Higher plant spacing: smaller basal area	Inoue et al. (2011)
6 forest tree species	Higher plant spacing: the plants showed higher growth	Nascimento et al. (2012)

Source: Personal (2017).

2.3.2 Wood properties

For a subject such as the effect of silviculture on wood properties, the only proper initial statement to make is that anything that causes a change in the growth pattern or form of a tree may result in differing 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 (MALLAN; HOON, 1992).

Wood properties are a function of genotype and environment (climate, site and silviculture), also they can vary between individual trees 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 determinism via the effects of ring width and cambial age on wood density (GUILLEY et al., 2004). Zobel and Van Buijtenen (1989) says that many research has been done on the relationship between wood density and growth rate. The growth pattern in the irrigated treatment, which favored production of a higher proportion of earlywood, resulted in wood with lower basic density than those of the non-irrigated trees (DOWNES et al., 2006).

Rocha et al. (2016), states that wider plant spacing tends to produce trees with denser woods in *Eucalyptus*.

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

The mechanical processing of wood of fast-growing *Eucalyptus*, the occurrence of cracking and warping is the main cause of low yields found in the production of lumber. These defects originate in the high growth stresses the trees. Growth stresses are those that develop inside the living tree trunks (DINWOODIE, 1966). Fewer studies have explored the influence of growth rate on wood mechanical properties (ZHANG, 1995).

The variations of wood properties depend on various factors, including silvicultural treatments applied to forest planting. Some examples of research showing these relationships are shown in Table 3.

Table 3 - Studies conducted analyzing the effect of silvicultural treatments on wood quality.

Specie	Silvicultural treatment	Major findings	Reference
Cedrus atlantica	Thinning	Higher plant spacing: the proportion of heartwood in the stem cross sections increased at all stem heights examined; the mean basic density decreases with the stem height in all examined stands	Hapla et al. (2000)
E.globulus	Plant spacing	Site had a highly significant effect on fiber length (increase from pith to bark); site had a highly significant effect on wall thickness and lume diameter (site with slowest growth: fibers with thicker walls and smaller lume diameter); the differences in chemical composition between provenances were statistically non-significant for all components except for extractive; Both provenance and site had a highly significant effect on pulp yield, but their interaction was non-significant	Miranda and Pereira (2002)
P.radiata	Thinning Fertilizer application	The trees that was applied thinned and 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	Wider spacings: higher levels of lignin and hemicellulose 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 variation of the MFA and MOE	Hein et al. (2016)
E.grandis x *E. camaldulensis*	Planting spacing	Wider spacing: tend to produce trees with denser woods	Rocha et al. (2016)

Source: Personal (2017).

2.4 SPATIAL VARIATION OF WOOD PROPERTIES ALONG STEM

The wood, whether analyzed in the radial, transverse or longitudinal sections, along the stem, have variation on the chemistry (composition, relative percentages, covalent bonding, etc.), mechanical, physical and anatomical properties, being therefore considered a heterogeneous materials (PAUL, 1963; MEGRAW, 1985; SJÖSTRÖM, 1993, cited by SAVIDGE, 2003). This variation occurs between species, although within the same species they also occur, mainly due to the age, genetic and environmental factors. Within the same species, there are significant variations in the height of the trunk (longitudinal) and toward the pith to the bark (radial). Furthermore, there are differences between the earlywood and latewood, heartwood and sapwood, and on a microscopic scale, between individual cells (KOLMANN; COTE, 1968).

Many silvicultural treatment can made changes on the wood quality, as Paul (1963) and Megraw (1985) affirmed valuable insight into how wood density and other wood quality features that can be manipulated through silvicultural treatment. As an example, the 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) points out that the choice of arrangements and spacings unsuitable for the species can intensify the competition and reduce the homogeneity of growth, which contributes to increase the number of trees and dominated lower utilization of available resources. According to Raymond (2002), the variation in wood, 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 predict accurately, since, according to Zobel and 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 the wood characteristics. The genetic makeup of the tree influences both competence for growth and the physico-chemical nature of growth. The environment that the tree grows in may serve to accelerate or retard growth competencies and otherwise modify the physico-chemical attributes arising during growth (SAVIDGE, 1996).

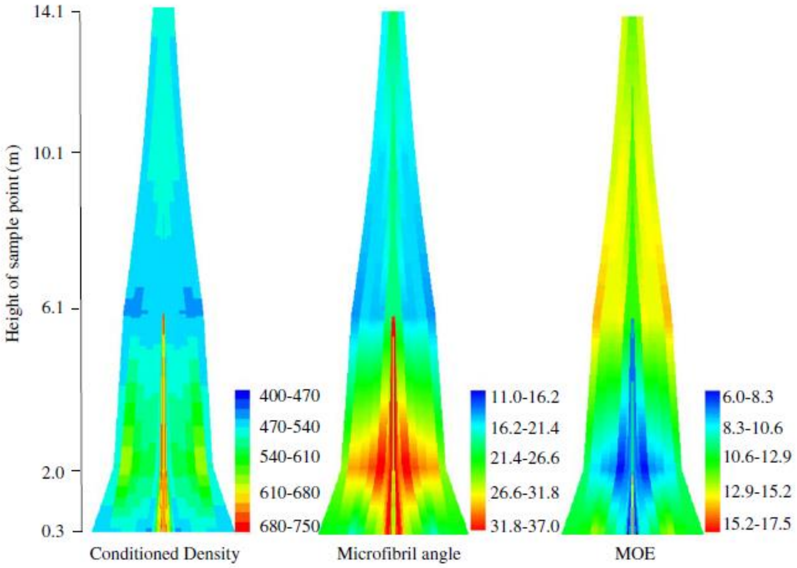
In view of this variation, the most commonly studied property is density (DOWNES; RAYMOND, 1997) as it is easy to measure and is related to many product performance issues, such as timber stiffness, strength, pulp and paper productivity (WIMMER et al., 2002).

On wood, the variations in 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). The variation in wood properties results from differences in the genotype of the trees and the environments in which they grow (site and climate) (MALIK; ABDELGADIR, 2015).

Wood density has been reported to exhibit variable patterns within trees both longitudinally and radially, therefore the measurement of this variation is made difficult in many eucalypts, due to the absence of annual ring structure that makes it difficult to resolve data into annual increments (SANDERCOCK et al., 1995). The most common trend observed is for density to increase with increasing tree height, sometimes accompanied by an initial decrease in the base of the tree. Where an initial decrease in density is followed by an increase with height, the minimum density occurs at the first sampling height above the base of the tree (RAYMOND; MUNERI, 2001).

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

FIGURE 1 - The within tree variation density (kg m^{-3}), microfibril angle (degrees) and stiffness (MOE) (GPa) in a 140-year-old spruce.



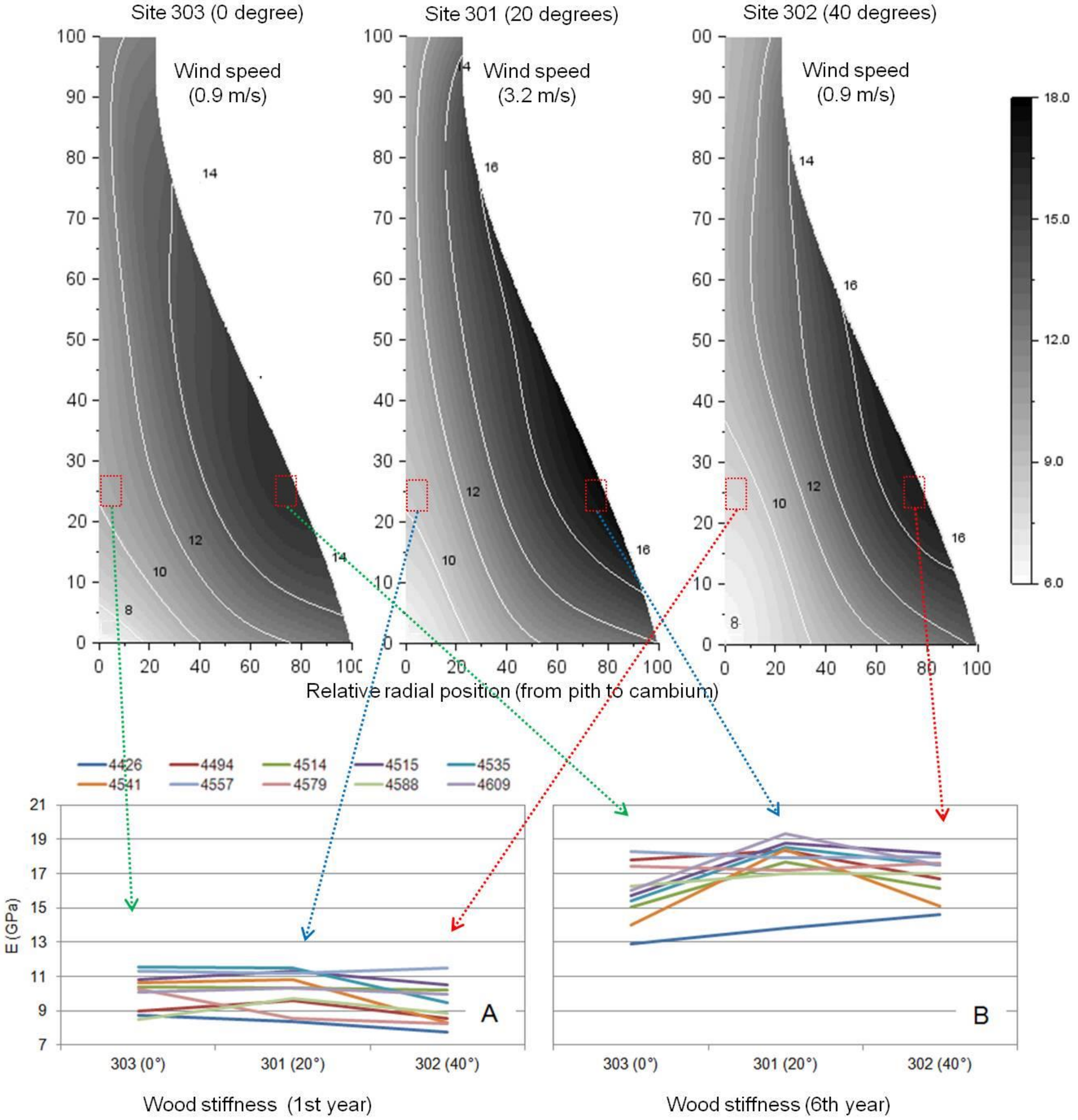
Source: (DOWNES, unpublished, cited by DOWNES et al., 2009).

Downes et al. (2014), analyzing 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 the air-dry wood density, MOE (modulus of elasticity) and KPY (Kraft pulp yield) all increased, on average, from pith to bark, while MFA consistently decreased from pith to bark on all treatments. The radial increases in KPY and cellulose content were also found 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. (2011a) evaluated the radial variation on the cellular dimensions of the wood of a 31-year-old *Tectona grandis* tree planted on tree 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. The wood density, MFA and MOE have the variation in the tree top lower because these woods were produced recently, months before harvesting. The authors says that the spatial variation of wood stiffness seems to be sensitive to two environmental conditions, and concluded that at the base and top of the trees there was no significant effect of growing conditions on the radial variation of the wood properties considered on them study, as shown on Figure 2.

FIGURE 2 - Relative spatial variation of modulus of elasticity (MPa) in *Eucalyptus urophylla* x *E. grandis* trees, highlighting the radial variation at 25 % of the tree height and the radial variation of the wood stiffness of clones at the clonal tests. Top mean value of all the studied clones. Bottom site interaction plot for each clone for the 25 % position; A represents wood produced at 1 year while B the wood produced at 6 years.



Source: HEIN et al. (2016).

On another research, Antony et al. (2015) conducted a study trying to identify geographical variation in loblolly pine bark and wood properties at the whole-tree level and to quantify the 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, the MFA decreases with height, reaching a minimum 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*, the MFA declines from pith to bark but unlike conifers, the angles are much lower close to the pith, typically 15–20°. Based on average trends for 29 trees, the 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. The ray area showed a relationship with ray density and ray height. The radial variation was explained by the effect of cambial age.

Downes et al. (2012), developed calibrations based on solid wood samples were constructed to describe radial variation in Kraft pulp yield and cellulose content using intact wood samples from *Eucalyptus globulus* Labill. from three sites with contrasting annual rainfall. They concluded that pulp yield and cellulose content were higher at the 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 the more productive sites was obtained steeper pith-to-bark increases in pulp yield than the driest site.

2.5 INFLUENCE OF PLANT SPACING ON THE VARIATION OF WOOD PROPERTIES

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

The plant spacing plays an important role in determining wood properties, its effects are species-specific (TONG et al., 2009). The differences in the wood produced at extremely wide and narrow initial spacings is less a matter of quality than quantity (LARSON et al., 2001). Hart (2010), shows that with increasing plant spacing occurs adverse effects on wood intended for structural purposes. In addition, increased spacing could potentially result on decrease the fiber length and increased knot size and frequency (MEHARI; HABTE, 2004). A dense initial spacing can be utilized and subsequently reduced in stand development.

The control of stand density, either through initial spacing or thinning or a combination of the two, 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, 2010).

A better understanding of the relationship between initial spacing and wood and the end product quality should help define improved 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 other study, Watson et al. (2003) have 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 widest spacing, the outer wood fiber length was significantly shorter than at the four tighter spacings. Fiber coarseness and cell wall properties were similar at all spacings. Garcia et al. (1991) concluded that the basic density shows a tendency to decrease with increasing spacing, while Rocha et al. (2016) found an increase of the density with rising spacing.

Moulin et al. (2015) evaluated a variation in the chemical composition of *Eucalyptus* hybrids at different ages (6 and 12 months) and plant spacing (3 x 0.5; 1.5 x 2; 3 x 1; 3 x 2; and 3 x 3 m). According to these authors, the plant spacing does not influence the chemical composition except for the lignin content. Trees growing at larger spacing tends to produce wood with higher lignin content. Similar findings were reported by Rocha et al., (2016), who studied *Eucalyptus grandis* x *E. camaldulensis* with 7-year-old in five different plant spacings: 3 x 0.5; 3 x 1; 3 x 1.5; 3 x 2; and 3 x 3 m. They also found that the basic density of the wood increase with large spacings.

Yang and Hazenberg (1994) studying the impact of spacing on tracheid length, relative density, and growth rate of juvenile wood and mature wood in 38-year-old trees of *Picea mariana* (Mill.) 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 smaller spacing and have no significant difference in the relative density between the two wider spacings was observed. The longest fiber lengths were found at the intermediate spacing, and the tracheid lengths of the larger plant spacing were significantly shorter than those of the other two spacings.

Downes et al. (2014), working with 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). The authors found that on the higher spacing the trees have increase on the basic density of the wood, no changes on MFA by plant spacing and the higher MOE on the smaller spacing. Lima et al. (2011b), analyzing 31-year-old *Tectona grandis* tree on different plant spacing (3 x 1.5; 3 x 2; and 3 x 2.5) concluded that the fiber length, fiber wall thickness and frequency vessel were influenced by spacing of planting.

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

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 rate of growth, which is influenced by initial spacing and the period to crown closure (CLARK; SAUCIER, 1991). The properties 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 the juvenile wood while alpha cellulose is lower (PASSIALIS; KIRIAZAKOS, 2004).

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

2.6 WOOD PROPERTIES

2.6.1 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, the density (basic density) is normally the first wood property to be assessed in a tree improvement program (LIMA et al., 2000).

Wood basic density, defined as the mass of oven-dry wood per unit volume 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 and Côté (1968), variations on density are due to differences in the wood anatomical structure and the amount of extractive substances per unit of volume, depending mainly of the age of the tree, genotype, site index, climate, geographical location and silvicultural treatments.

The variations in density are dependent on changes in the proportion of vessels and the thickness of the cell walls of the fibers. The increase in density may be the result of the increasing cell wall thickness of fibers or an increase in the proportion of the fibers in relation, for example, with 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).

The 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 of *Eucalyptus* trees, their density alone accounted for 81 percent of the variation in their MOE (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).

Hein et al. (2013) claim that there are numerous declarations that the density is the most important feature in determining the properties of the wood, since it is associated with many mechanical properties including elasticity and breaking module (MOE and MOR, respectively). As the density increases, the strength properties tend to increase. However, the density does not explain by itself the mechanical behavior of wood.

2.6.2 Wood stiffness

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

The stiffness of the wood, in hardwood species, are strongly influenced by their basic density (INNES, 2007; NICHOLSON et al., 1975), but the cellulose microfibril angle, lignin proportion and the extent of spiral grain also influence on the stiffness of the wood (HUANG et al., 2003; NICHOLSON et al., 1975).

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

Hoibo and Vestol (2010) state that although there have been several important studies of mechanical properties 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 describe exactly.

According to Hein et al. (2010a) the main objective of *Eucalyptus* breeding programs is designed for the pulp and paper industry producing varieties of trees with high levels of cellulose with the least possible amount of lignin. The mechanical properties of wood are not considered in these breeding programs, which causes that the trees are more fragile and susceptible to breakage, which may be a serious problem in the field.

2.7 NON-DESCTRUCTIVE EVALUATION OF WOOD

Typically, the wood characterization is done by traditional and destructive analysis of samples, using specific equipment and done on slow way, standard-based testing routines and capable of providing reliable results (ROSS; PELLERIN, 1994). However, this type of assessment requires a long lead time between preparing samples and arriving at final values for the relevant property.

Nondestructive evaluation of the properties of wood 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 theory of elasticity and of the instrumentation for the measurement of wood properties (BUCUR, 1995).

The nondestructive evaluation of wood for determining their 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).

According to Bucur (2003), one criterion of classification of non-destructive techniques is the characteristic wavelength of the radiation that interacts with wood specimen (X-ray, infrared, microwave, ultrasonic, nuclear magnetic resonance).

Several researches have been developed in order to predict properties of wood by nondestructive methods. The studies presented by Schimleck et al. (1999), Raymond and Muneri (2001), Downes et al. (2002), Jones et al. (2006), Hein et al. (2009a), Hein et al. (2009b), Andrade et al. (2010), Hein et al. (2010a), Hoibo and Vestol (2010), Hein et al. (2010b), Couto et al. (2012), and Downes et al. (2012) are some examples of using nondestructive methods in assessing the timber properties.

Currently, there is great demand for fast and reliable methods for selecting and woods classification, both by geneticists as the mechanical processing industries (YANG; EVANS, 2003). The nondestructive methods or tests have great potential as analysis tools, since they are intended to qualify the material without jeopardizing its future use (COUTO et al., 2012). Most of research have been conducted into alternative methods for fast and reliable wood characterization that, along with traditional methods, can result both in analysis quality and time gains (ANDRADE et al., 2010).

Among the several nondestructive methods, the resonance or transverse vibration method and the near infrared spectroscopy (NIR) can be considered.

2.7.1 Resonance

The resonance method consists in vibration analysis of a sample timber, obtaining the modulus of elasticity of the material from the analysis of the main vibration frequencies (BRANCHERIAU; BAILLERES, 2003). Commonly referred to as "resonance method" in the international literature, this technique has stood out among the employed in non-destructive testing, 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 the Young, the shear modulus and the loss tangent) of the wood even in lumber containing knots, small cracks and also slightly damaged areas.

The transverse vibration method has stood out among those used in non-destructive testing, especially for strong adhesion between the physical phenomenon model and the corresponding theoretical mathematical model (CALIL JÚNIOR; MINÁ, 2003). Vibration analysis is a simple and efficient way of characterizing the elastic properties of a mass (BRANCHERIAU; BAILLERES, 2003).

According to Murphy (2000) cited by Nogueira and 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 also wooden panels. The natural frequency of vibration of the material is correlated with its stiffness in bending (CARREIRA; CANDIAN, 2008).

The 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 frequency of vibration. For a vibrating beam of given dimensions, the natural frequency of vibration 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 frequency of vibration of prismatic bars and the mathematical relationships existing between the two (MALHOTRA; SIVASUNDARAM, 2004).

According to Candian and Sales (2009), the first transverse vibration test using the technique was done 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 constants values obtained in dynamic tests with values resulting from static tests.

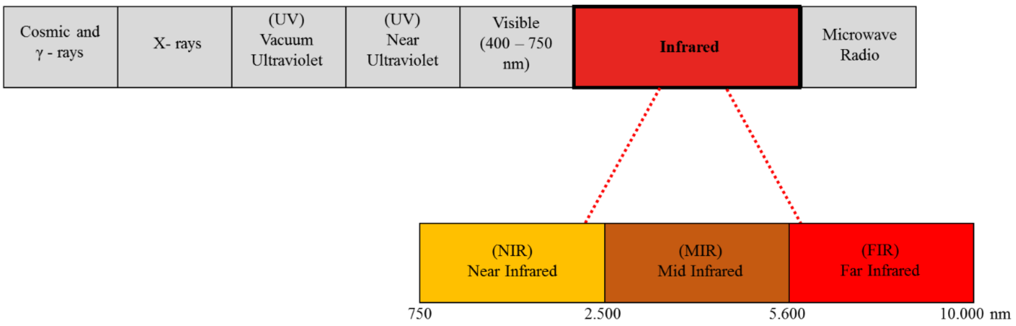
Several authors have reported studies using resonance method to determine wood properties, as Halabe et al. (1997), Haines et al. (1996), Haines and Leban (1997), Ilic (2001), Burdzik and Nkwera (2002), Wang et al. (2002), Liang and Fu (2007), Chauhan et al. (2007), Carreira and Candian (2008), Canadia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

2.7.2 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 the NIR is focused on the agricultural and food industries (MARTEN et al., 1985).

According to Pasquini (2003), the NIR is the measurement of the intensity of the absorption / reflection near infrared light (in the range of 750 to 2500 nm) (Figure 3), in relation to the wavelength held by the sample.

FIGURE 3 – Electromagnetic spectrum, showing the position of the infrared region relative to visible light.



Source: Personal (2017).

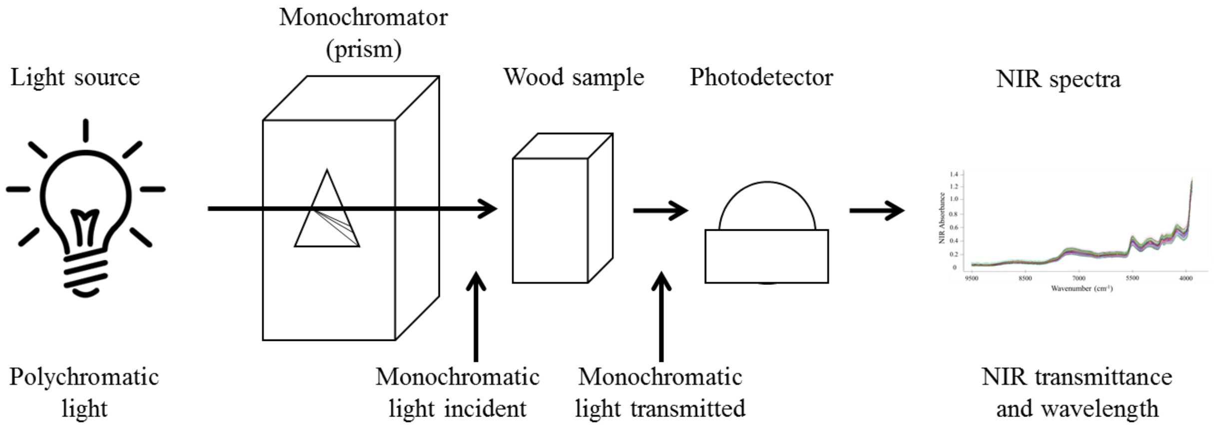
NIR spectroscopy analysis is a fast, environment-friendly analytical method that has gained widespread acceptance in recent year. It is based on vibrational spectroscopy that monitors changes in molecular vibrations intimately associated with changes in molecular structure. Spectra within the NIR region 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).

The analytical methods derive from the use of the NIR spectroscopic region 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), the 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 the NIR works from theory that radiation of a given frequency, capable to supply exactly the energy between two vibrational levels or of their overtones or combinations of two or more vibrations, can be absorbed by the molecule and can produce excitation to a higher vibrational energy level. The same author says that the match of radiation energy with the energy difference between two vibrational levels causes a selective response of the molecular system to the incident radiation. It means that in a given wavelength range, some frequencies will be absorbed, others (that do not match any of the energy differences possible for that molecule) will not be absorbed while some will be partially absorbed. This complex figure of the intensity of absorption versus wavelength constitutes the absorption spectra of a substance or sample.

Figure 4 shows the simple physical principles of the spectrometer.

FIGURE 4 – Schematic of NIR spectrometer readings.



Source: Personal (2017).

The spectrometer scheme shown in Figure 4 is of a dispersive apparatus operating in transmittance mode, however, there are also spectrometers equipped with sensors that measure the amount of light absorbed or reflected by the material. Nowadays, infrared spectroscopy equipment has reached a high level of sophistication (Fourrier transform, integration sphere, etc.) and dispersive devices using monochromators are deprecated.

Since the 1980's, this technique has been used to estimate various wood properties, however, since 1990's many studies come to show how it works, as showing the Table 4.

TABLE 4 - 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 and Schoberl (2001)
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 and 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)

Wood property	**Specie**	**Statistical model (R^2/ *R)**	**SECV/ *RMSECV**	**Reference**
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 grandis* x *E. urophylla* hybrids	0.81	1.149*	Hein et al. (2010c)
Lignin (%)	Seven species of pines	0.95	0.44	Hodge and Woodbridge (2010)
Cellulose (%)		0.72	1.10	
MOE (MPa)	*Pinus* spp. Veneers	0.78^*	841	Carneiro et al. (2010)
Basic density (kg. m^{-3})	*Eucalyptus grandis* x *E. urophylla* hybrids	0.78	23.8	Hein et al. (2012)
Radial shrinkage (%)		0.46	0.96	
Tangential shrinkage (%)		0.46	1.22	
MFA (degrees)		0.75	1.31	

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

Source: Personal (2017).

As the spectral absorbance data is associated with more than one frequency at the same time these are analyzed by multivariate statistics, where you can model various properties of the material from their spectroscopic data (WILLIAMS, 1987).

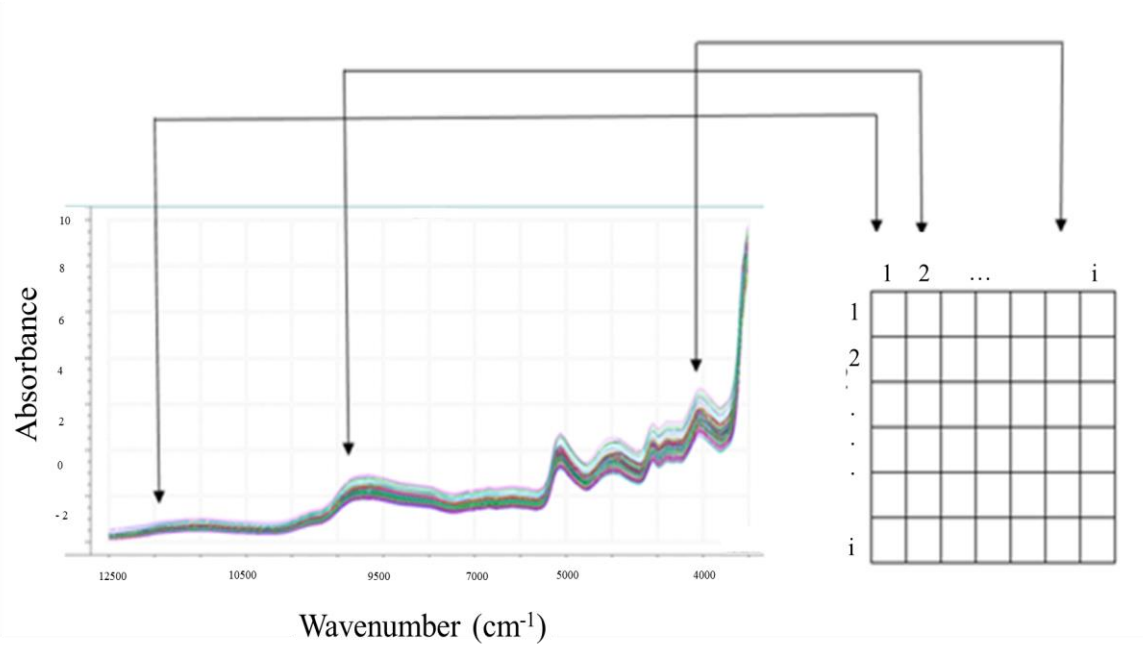
According to Marten and Naes (2002), a multivariate linear model can be represented as a mathematical function that represents the relationship between X and Y, as follows:

$$y = b_0 + \sum_{k=1}^{k} b_k x_k + f \tag{Eq.(1)}$$

Where *k* represents the number of variables in the equation, and *f* is the error.

In this type of calibration measurements the instrumental X are represented in the form of a matrix, while the property of interest Y, which is determined by a standard method, is represented by a vector (VALDERRAMA et al., 2009). Figure 5 shows an example construction of a matrix X.

FIGURE 5 - Schematic illustration of the construction of a matrix.



Source: Personal (2017).

Martens and Tormod (1989) stated that in order to minimize the occurrence of outlier samples, various pretreatment methods have been used, as standards, logarithmic transformation, baseline correction, calculating the derivative, multiplicative correction signal, scaling and digital filtering for noise removal. The transformation of the original data through the pretreatments, as well as contributing to the data to be symmetrically distributed, corrects the aspect ratio between the matrix X and Y so that the models fit better and provide a more uniform precision (PASQUINI, 2003).

Multiple regression methods are currently employed in the multivariate calibration, and the most used for linear regression modeling are the Principal Components Regression (PCR) and Partial Least Squares (PLS) (NETO et al., 2006).

The multivariate calibration is one of the areas of chemometrics, can be defined as operations to establish a relationship between response and factors, or, for example, between instruments, and measures a property of interest (BRERETON, 2003). The calibration set that is sufficient to develop and evaluate a calibration model should provide all of the likely sources of variance.

According to Pasquini (2003), a validation can closely resemble a calibration. The fundamental difference is that the test samples are not used to fit the model, only to verify the performance of the model performs new data. Model validation is indispensable after calibration of any property of a material analyzed by spectroscopy (GEMPERLINE, 2006).

A model may have its validation performed by two methods, namely, the external validation and cross-validation (WORKMAN; WEYER, 2007).

In cross-validation, one or more samples are removed from the calibration model samples and used as a set of prediction. It is suggested that the cross-validation is used only when the number of samples is limited in cases that the cost of laboratory tests is high (PASQUINI, 2003).

The external validation is characterized by extracting the random number calibration set samples, what is called a validation set. The remainder of the samples is done and calibration is obtained by the regression equations to predict the validation samples. The calibration is then used to estimate the value of the validation lot properties from their near infrared spectra. Thus, it is then possible to compare the estimated values with the values determined in the laboratory (BURNS; CIURCZAK, 2008).

3 MATERIAL AND METHODS

3.1 ORIGIN OF THE MATERIAL

The trees were obtained in experiments conducted by the company Plantar Reflorestamentos located in the city Brasília de Minas, Minas Gerais, Brazil, owned by the company TTG Brazil Investimentos Florestais, to evaluate the survival and growth of *Eucalyptus* clones under different planting spacing. The city is located in the northern region of Minas Gerais state, approximately 106 and 533 km of the municipalities Montes Claros and Belo Horizonte, respectively. The average altitude is approximately 900 m and the annual rainfall is about 1000 mm (COPASA / MG, 2011). The soil is a Red Yellow Latossol, medium texture and the flat relief. The average altitude of this place is 900 m and the annual rainfall around 1000 mm.

3.2 SILVICULTURAL TREATMENT/DESIGN

The experiment was installed in December 2003, and the trees were harvested at 12 years-old. Four different hybrids of *Eucalyptus urophylla* clones (i144, GG100, 2486 and i182) growing in three plant spacing's (3 x 3, x 3 x 4 and 3 x 8 m) were investigated.

The experiment was mounted at a randomized block design in a factorial design and 3 (three) repetitions per treatment were used, totaling 36 (thirty-six) trees analyzed in this study. The trees were selected from the average diameter of the trees in each treatment (TABLE 5).

Table 5- Average diameter and height for in 12-years-old *Eucalyptus* clones at different plant spacing.

Clone	Plant spacing (m)	Average diameter (cm)	Average Height (m)
i144	3 x 3	18.44	21.68
	3 x 4	18.42	20.07
	3 x 8	24.58	22.77
GG100	3 x 3	19.19	19.80
	3 x 4	19.99	19.18
	3 x 8	23.17	22.93
2486	3 x 3	19.10	20.37
	3 x 4	18.18	21.70
	3 x 8	21.84	21.55
i182	3 x 3	18.21	21.20
	3 x 4	17.95	18.81
	3 x 8	22.57	21.66

Source: Personal (2017).

The experimental planting area consisted of eight different clones in the three different plant spacing. However, due to the mortality rate present in some areas, only clones where there was no mortality were used. In all cases, the trees of the borders were disregarded.

To characterize the material 6 discs were collected at each tree, at the BH (breast height), 0, 25, 50, 75, 100% of the commercial tree height and one log from each tree, located between the disc from the base and the BH. For selecting the trees used in this study, we made previously an inventory for each plot and it was collected those trees that had the average diameter at breast height (FIGURE 6).

FIGURE 6 – a) Selection of the trees; b) collecting of the discs and logs, c) sampling.

(a) (b) (c)

Source: Personal (2017)

3.3 SAMPLING PREPARATION

The preparation of the samples were performed on the wood discs and logs sampled.

3.3.1 Wood discs

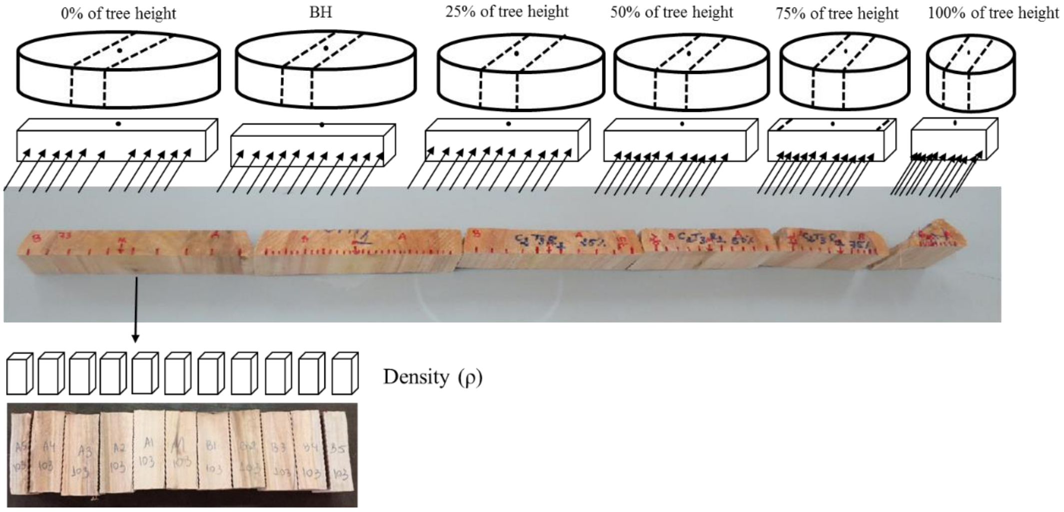
From each disc, a radial strip from pith to bark (FIGURE 7) was removed by a vertical band saw and after by a circular saw, and its radial surfaces were sanded with 300-grit sandpaper for approximately 30 s. The radial strips were marked randomly but well distributed from pith to bark to supply tangential sections, as parallel as possible, to the growth rings for measurements to obtain the spectra and subsequent determination of the density. These wood strips had variable height, length and width (depending on the circumference and thickness of each wood disc). After sectioning, the samples were kept in a climate-controlled room (temperature around 20°C and relative humidity around 65%). Under these conditions, the moisture content of the wood samples stabilized at 12%.

FIGURE 7 – Removal of the radial strip from pith to bark by a vertical band saw and after by a circular saw, from each disc.

Source: Personal (2017).

To obtain spectra of the strip removed from the disc sections, there were marked points to do the readings of the spectra. The markings were made from 1 cm from the far end and 1 cm from the marrow to the two sides. On the strip removed from the discs from the heights 0, BH, 25, 50, 75 and 100% were conducted five measurements on each side. After completing the reading on the near infrared spectrum, the strip from each disc removed from the 0% height was sectioned in the same markings made for reading of the spectra, to determine the wood basic density (FIGURE 8).

FIGURE 8 – The markings taken on the strips and the strip from the disc removed from the 0% height sectioned in the same markings made for reading of the spectra for basic density determination.



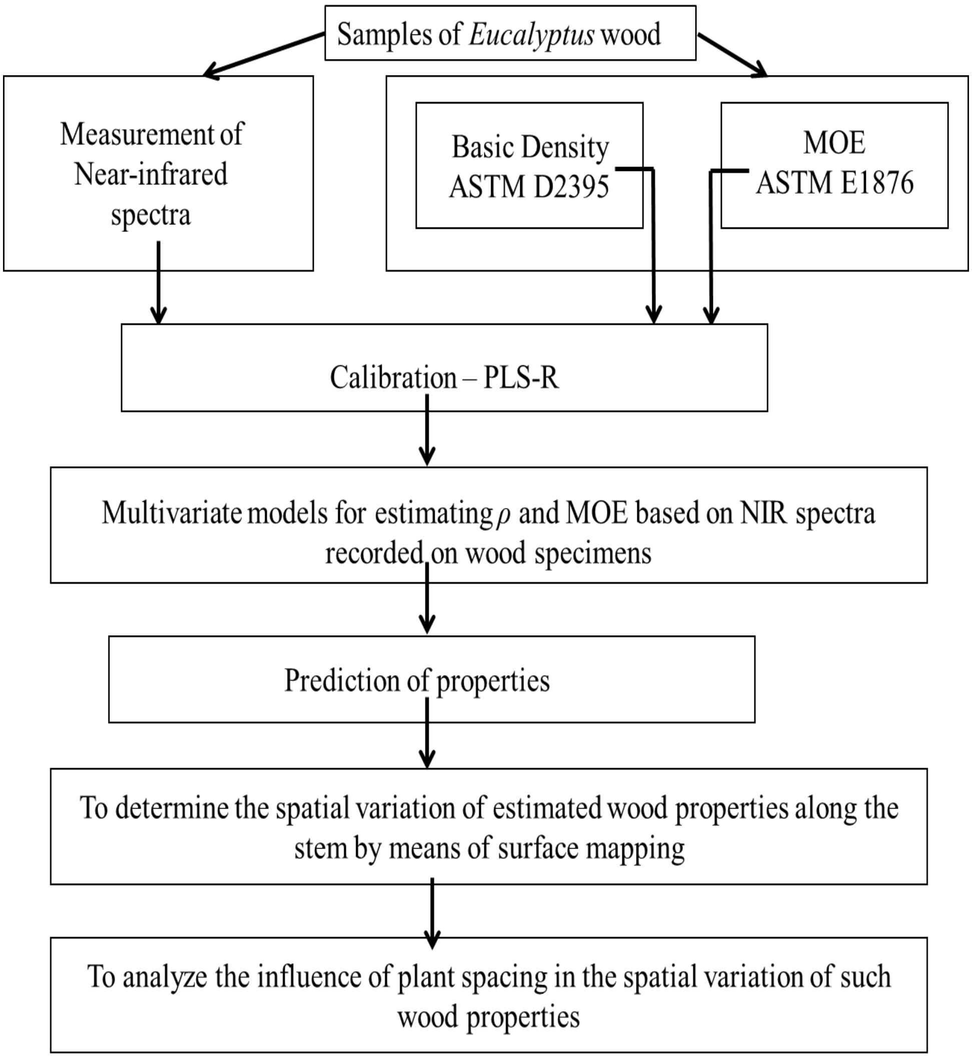
Source: Personal (2017).

3.3.2 Specimens from logs

Two hundred and twenty-five (225) clear wood specimens were cut from central boards of the logs (25 mm × 25 mm × 410 mm in the R, T and L axis, respectively). After cutting, they were conditioned in a climatic room at 20°C and 65% of relative air humidity to maintain the moisture content constant at a theoretical value of 12%. The specimens were submitted to dynamic test for obtaining the modulus of elasticity (MOE). The spectra were acquired on the transverse face of the specimen, two of which were obtained at both ends and one at the center, totaling three spectra per specimen.

A general and simplified procedure for predicting properties from spectral data and the entire procedure used in the execution of this study is presented in Figure 9.

FIGURE 9 - Procedure for properties prediction from spectral data.



Source: Personal (2017).

With this methodology, one can estimate these properties of the standing tree wood, using a data for the removal of a sample.

3.4 CARACTERIZATION OF THE WOOD

3.4.1 Physical property: Basic density

The density (ρ) of the wood samples was measured according to the ASTM D2395 (ASTM 2002). The formula for calculating the basic density is given as follows:

$$\rho = \frac{\text{oven-dried weight}}{\text{green volume}} \qquad \text{Eq. (2)}$$

The green volume of a piece of wood was determined by water displacement according to the principle of Archimedes. The samples were first soaked in water to reach the saturation. An experimental dispositive was used for measuring the green volume of the samples (FIGURE 10a). The digital dispositive was used again for precisely measuring the dry weight (FIGURE 10b). Thus, the basic density of wood was calculated.

FIGURE 10 - Experimental dispositive for measuring the green volume of the samples (a) and the sample dry weight (b).

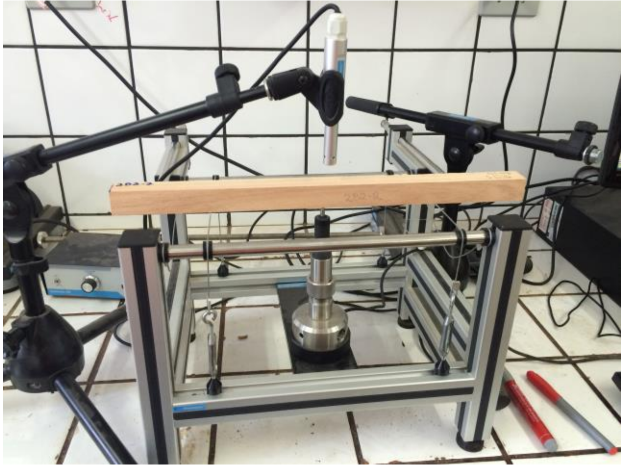
(a) (b)

Source: Personal (2017).

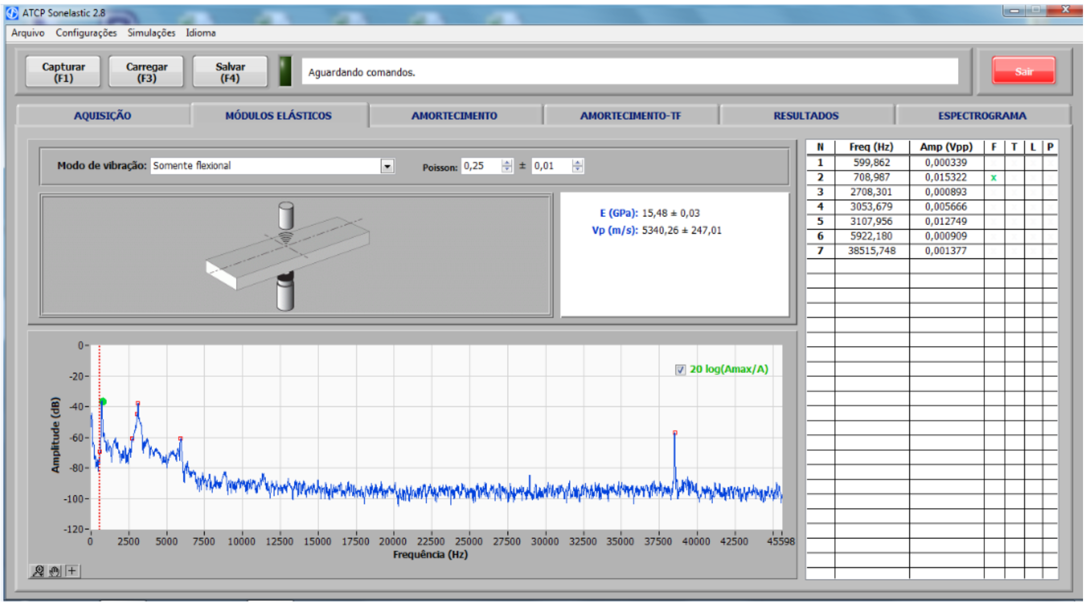
3.4.2 Mechanical property: Wood Stiffness

The determination of the dynamic elastic modulus (MOE) was performed by analyzing the flexural natural frequencies of vibration using the Sonelastic® equipment (ATPC) (FIGURE 11).

FIGURE 11 – (a) Sonelastic experimental device, (b)Sonelastic software screen showing vibration peaks when measuring MOE.



(a)



Aguardando comandos.

Modo de vibração: Somente flexional

Poisson: 0,25 ± 0,01

E (GPa): 15,48 ± 0,03

Vp (m/s): 5340,26 ± 247,01

☑ 20 log(Amax/A)

N	Freq (Hz)	Amp (Vpp)	F	T	L	P
1	599,862	0,000339				
2	708,987	0,015322	x			
3	2708,301	0,000893				
4	3053,679	0,005666				
5	3107,956	0,012749				
6	5922,180	0,000909				
7	38515,748	0,001377				

(b)

Source: Personal (2017).

The calculation of MOE in the flexural vibration mode was performed by means of Eq. (3) as described in E1876 procedure (ASTM, 2007). Where E is the dynamic modulus of elasticity; *m* is the mass of the test sample (in g); *L* is the length (in mm), *b* is the width (in mm) and *t* is the specimen height (in mm); *ff* is the fundamental resonant frequency flexural

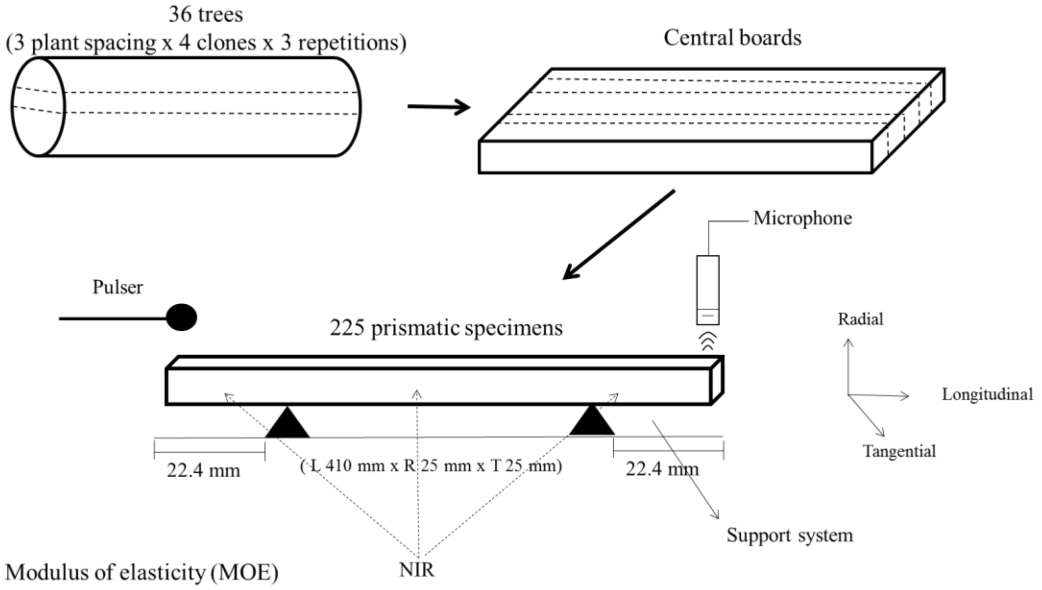
(Hz); *T1* is a correction factor for the fundamental mode flexural, which depends on the Poisson ratio (μ) and the aspect ratio of the test sample given by Eq. (3).

$$MOE = 0.9465\ (m.f).b)\ .\ (L\ .t)\ .T1 \qquad \text{Eq.(3)}$$

$$T1 = 1 + 6.585\ .(1 + 0.0752\ .\mu + 0.8109\ .\mu^2)\ .(t^2\ .L^{-2}).2 - 0.868\ .(t^4\ .L^{-4}) - [(8.34\ .(1 + 0.2023\ .\mu + 2.173.\mu^2).(t^4.L^{-4})).(1 + 6.338.(1 + 0.1408\ .\mu + 1.536.\mu.(t^2.L^{-2}))^{-1}].\alpha \qquad \text{Eq. (4)}$$

The prismatic test samples had nominal dimensions of 25 mm x 25 mm x 410 mm (FIGURE 12).

FIGURE 12 – Sampling procedure and measurement protocol.



Source: Personal (2017).

In this technique, the MOE is calculated from the sound emitted by the specimen under a small mechanical stroke. This sound, or acoustic response, is composed of the natural frequencies of vibration of the body that are proportional to the MOE and their amplitude decays according to the damping of the material.

For simple geometries, such as the samples used in this experiment, there is a univocal relation between the natural frequencies of vibration with the dimensions, mass and MOE of the specimen. Dimensions and mass are easily measurable parameters with a pachymeter and scale. Knowing the dimensions, the mass and the natural frequencies of vibration, the calculation of the MOE is immediate.

3.4.3 NIR spectral acquisition

A Near Infrared spectrometer (Bruker, model: MPA) was used for spectral acquisition. This equipment uses the Fourier transform and has an integrating sphere which measures the diffuse reflected light. This integrating sphere (150 mm^2 spot) collects light from all angles; thus, the effects of wood texture and other non-homogeneities are minimized.

The acquisition of the spectra occurred in the range of 12.500 to 3.600 cm^{-1}, but the range of the spectral region between 12.500 to 9.500 cm^{-1} was excluded because it was not informative and presented noises, so the absorbance peaks can be observed in the range between 9.500 to 3.600 cm^{-1}.

It was used the diffuse reflectance mode, with spectral resolution of 8 cm^{-1} and 64 scans per reading. The spectra were obtained in a climate-controlled room, with temperatures around 20 °C and relative humidity around 60%.

3.5 MULTIVARIATE MODELLING

3.5.1 Calibration, validation and model selection

The partial least squares (PLS) regression was used to establish the correlation between the spectral information and the wood properties using the Software The Unscrambler® version 9.7.

The Unscrambler program were used to adjust the models and to define the number of major components that were adopted, and this value should decrease the standard error of cross validation (SECV) and increase the coefficient of determination of cross-validation (R^2cv).

To validate the model calibration it was used the method of cross-validation. The anomalous samples (outliers), high leverage, residues were identified in graph and excluded during the adjustment of the templates to have a quality calibration.

The statistical parameters used to select the best prediction models were: coefficient of determination of cross validation model (R^2cv); standard cross validation error (SECV); standard deviation from performance ratio (RPD) and number of latent variables used in the calibration (LV). The RMSECV measures the efficiency of the calibration model to predict the property of interest in many unknown samples. The RPD is a way to identify the accuracy of the calibration and is the ratio between the standard deviation of the reference values and standard of cross validation error (RMSECV).

The PLS-R calibrations were performed in full cross-validation mode with a maximum of eight latent variables (LV), for ρ and MOE.

The final number of LVs adopted for each model corresponded to the first minimal residual variance and the outlier samples were identified from the Student residuals and leverage value plot analyses. To compare calibration and validation, the following statistics were examined: (i) Coefficient of determination of calibration set (R^2c), cross-validation set (R^2cv) or prediction set (R^2p); (ii) Root mean square error of calibration (RMSEC), cross-validation (RMSECV) or prediction (RMSEP); (iii) Ratio of performance to deviation (RPD) and (iv) Number of latent variables (LV). The general formulas for RMSEC, RMSECV and RMSEP are given in Burns and Ciurczak (2008) and can be calculated as follows:

$$RMSEC = \sqrt{\frac{\sum_{i=1}^{N}(\hat{y}_i - \hat{y}_i^2)}{N-A-1}} \qquad \text{Eq. (5)}$$

$$RMSECV = \sqrt{\frac{\sum_{i=1}^{N}(\hat{y}_{CV\,i} - \hat{y}_i^2)}{N-}} \qquad \text{Eq.(6)}$$

$$RMSEP = \sqrt{\frac{\sum_{i=1}^{Np}(\hat{y}_i - \hat{y}_i^2)}{Np}} \qquad \text{Eq. (7)}$$

where the y_i's are obtained by testing the calibration equation directly on the calibration (or cross-validation- y_{cv}) data, A is the number of latent variable, N is the number of samples of calibration set, Np is the number of samples of the prediction set. RMSEC, RMSECV or RMSEP should be as low as possible where as coefficient of determination should be high. The RMSEC statistic is a useful estimate of the optimal accuracy obtainable for a given set of wavelengths used to develop a calibration equation, while the calculation of RMSECV is a method useful for determining the "best" number of latent variables to use in building a calibration equation by cross-validation and it is an estimate of the RMSEP. The crossvalidation (CV) method is based on an iterative (repetitive) algorithm that selects samples from a sample set population to develop the calibration equation and then predicts on the remaining unselected samples (WORKMAN; WEYWER, 2007). RMSEP allows the comparison between NIR-observed predicted values and laboratory values (reference values) during the validation test with independent sample set.

The RPD value is the ratio of the RMSECV or RMSEP to the standard deviation (Sd) of the crossvalidation or validation sample set and can be calculated as follows:

$$RPD = \frac{Sd}{RMSE} \qquad \text{Eq. (7)}$$

This statistic provides a basis for standardizing the RMSECV (WILLIAMS; SOBERING, 1993) and makes possible a comparison of different calibration parameters such as spectral information obtained from different wood faces.

3.5.2 NIR modeling

NIR spectra were recorded for all wood specimens to calibrate and validate NIR-based models for predicting basic density (ρ) and MOE of wood samples.

Several mathematical treatments were tested, however, to suppress part of the noise and to improve signal quality, the SNV and first derivative pre-treatments were used in the spectral information of the basic wood density, and normalization, SNV and first derivative, for the MOE values. First derivatives (13-point filter and a second order polynomial) were applied on the NIR spectral data by the Savitsky and Golay (1964) algorithm to enhance the quality of the calibrations. According to Giordanengo (2005), pre-treatments are often applied to the data to avoid possible measurement errors that may occur due to differences in optical path of light, differences in sample density and other sources of variation. The pretreatment was done with the purpose of excluding noise and improve the quality of the calibration signal. Samples classified as outliers were not included in the calibration and validation phase of the models.

For the validation of the calibration equation, the methods of cross-validation were adopted. In the cross-validation of the basic density model, the sampling was divided into 8 calibration segments, and in each segment fifty-four samples were selected (at random) for

Validation of the model. In the cross-validation of the model for MOE, the sampling was divided into 8 calibration segments, and in each segment eighty-four samples were selected (random) for validation of the model.

The determination of the calibration and validation parameters was based on preliminary analyzes.

The criteria adopted to select the prediction models followed the recommendations described in Hein et al. (2009) and were as follows: (i) coefficient of determination of the model in the cross-validation (R^2cv) or independent validation (R^2p); (ii) standard cross-validation error (RMSECV) or independent validation (RMSEP); (iii) number of latent variables (LV) used in the calibration and (iv) ratio of performance to deviation (RPD).

3.5.3 Mapping of the wood properties variation

2-D plots presenting the spatial variation of wood traits were developed using the Scilab software (v.6.0.0). As NIR models were used to estimate wood traits on specific points along the tree trunk, data were interpolated using the cubic spline method to create estimates in a whole tree making it possible to build the surface graphics of the wood traits.

For the elaboration of the maps the average of the values of density and MOE obtained in the prediction for all radial section of the trunk was used, that will be represented by only one side of the trunk.

3.6 STATISTICAL ANALYSIS

The main advantage of PLS method is their ability to compress the relevant spectral information into a few latent variables; the orthogonality between these variables ensures the stability of the obtained model (JOUAN-RIMBAUD et al., 1996). In order to analyze NIR spectra information, PLS regression is of particular interest because it can analyze the data strongly collinear (correlated), with noise, with many X-variables (NIR spectra), and also, simultaneously, several variables can shape-response Y (WOLD et al., 2001).

The Martens' uncertainty test (WESTAD; MARTENS, 2000) was used to select the wavenumbers with regression coefficients significantly different of zero in order to develop more robust and reliable PLS models.

For the analysis of the results, the variance test were performed, considering the experiment as factorial 3 x 4 being 3 plant spacing and 4 clones. Software R, version 2.13.1 and ExpDes statistical package were used. The averages were compared using the Tukey test at 5% significance.

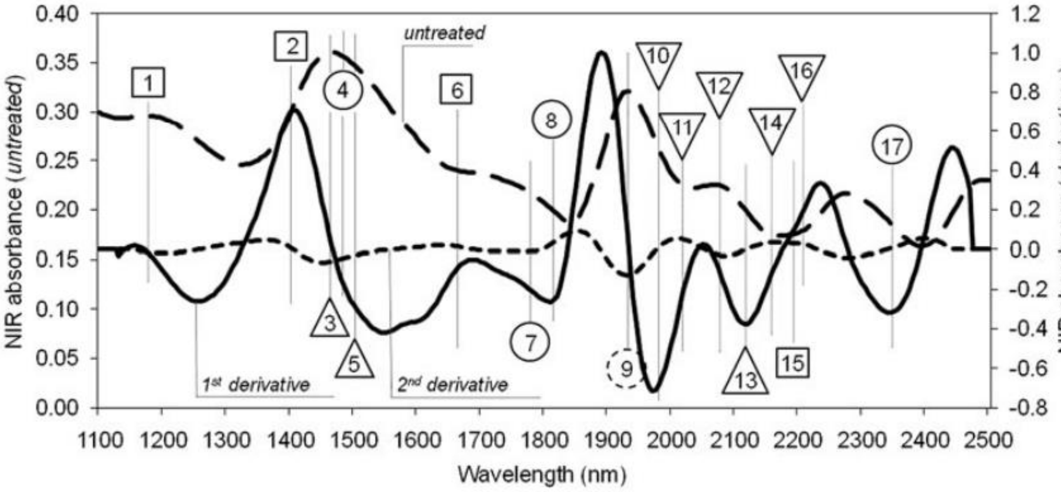
4. RESULTS AND DISCUSSION

4.1 NIR SPECTRA

Due to its composition, cellulose, hemicelluloses, lignin, extractives and inorganic, wood is classified as a complex three-dimensional biopolymer (KOLLMANN; CÔTÉ, 1968). The NIR spectra, obtained in the sphere of integration, reflect the energy absorbed by chemical bonds from different wood components, including their contents and interactions.

The Table 6 refers to the numbers assigned to the absorption bands presented in Figure 13. In this figure, the bands correspondent to lignin are shown by squares, to cellulose by full circles, to water by dotted circles and to resin by triangles.

Figure 13 - Absorbance versus wavelength plot for an untreated NIR spectrum and first and second derivative of the NIR spectrum showing bands assigned to chemical compounds. The scaling factor of the secondary y-axis derivatives was of 10^{-2}. The bands assigned to lignin are shown by squares, to cellulose by full circles, to water by dotted circles and to resins (adhesives) by triangles.



Source: HEIN et al. (2011b).

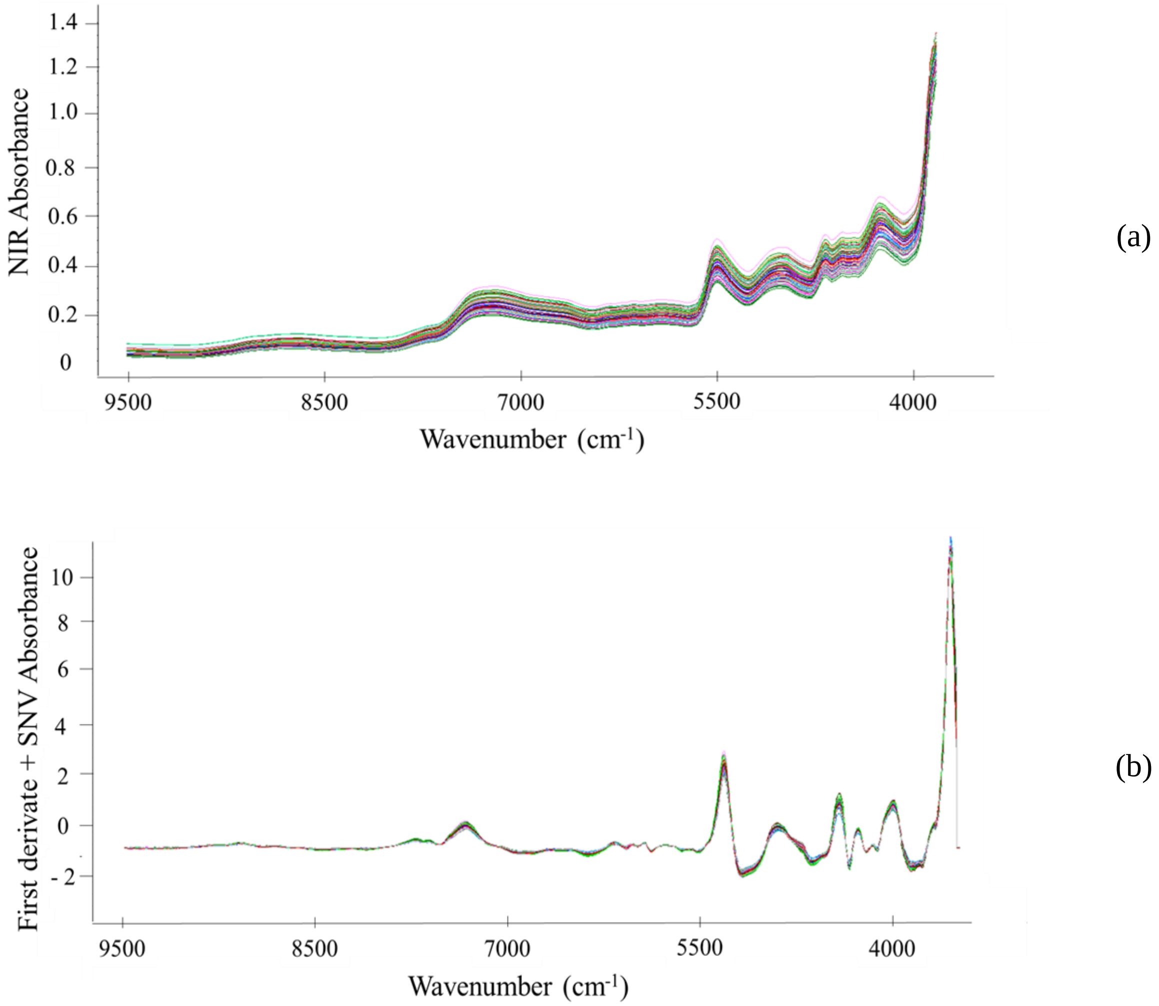
Table 6- NIR absorption bands assigned to cellulose, lignins, resins and water contained in agro-based particleboards. Numbers assigned to the bands and regression coefficients presented in Figure 14.

nm	Bond vibration	Structure	Index
1170	2nd overtone asymmetric stretching CH, HC=CH	Lignin	1
1360	CH deformation + CH stretching 2nd overtone	CH_3	-
1410	OH stretching 1st OT lignin or first overtone of an O–H stretching vibration of phenolic hydroxyl groups	Lignin	2
1417	C–H combination, aromatic associated C–H	Lignin	2
1428	1st overtone OH stretching (amorphous region in cellulose)	Cellulose	-
1470	1st overtone NH asymmetric stretching	Resin	3
1485	1st overtone NH symmetric stretching	Resin	3
1490	1st overtone OH stretching	Cellulose	4
1500	1st overtone NH asymmetric + NH symmetric	Resin	5
1548	1st overtone OH stretching (crystalline regions in cellulose)	Cellulose	-
1672	1st overtone CH stretching	Lignin	6
1685	1st overtone CH stretching (aromatic associated CH)	Lignin	6
1724	1st overtone CH stretching	Hemicelluloses	-
1780	1st overtone CH_2 stretching	Cellulose	7
1820	OH stretching + CO stretching 2nd overtone	Cellulose	8
1830	OH stretching + CO stretching 2nd overtone combination	Cellulose	8
1940	OH combination of the asymmetric stretching and bending	Water	9
1980	OH stretching + OH deformation combination band	Water	-
1990	Asymmetric NH stretching + amide II combination band	Resin	10
2040	Symmetric NH stretching + amide II	Resin	11
2080	Asymmetric NH stretching + amide III	Resin	12
2110	not assigned	Resin	13
2180	Symmetric NH stretching + NH_2 rocking and/or 2nd overtone amide I + amide III	Resin	14
2200	CH stretching and C=O combination	Lignin	15
2220	Symmetric NH stretch + NH_2 rocking	Resin	16
2335	CH stretching + CH_2 deformation combination band (and 2nd overtone of CH_2 streching)	Cellulose	17
2347	CH (1st overtone CH_2 symmetric stretching and δ CH_2) combination	Cellulose	17
2352	CH bending and stretching combination band	Cellulose	17
2461	CH stretching + CC stretching	Cellulose	-

Source: HEIN et al. (2011b).

Figure 14a illustrates the untreated NIR spectra measured and 14b the NIR spectra treated with First derivate and SNV of 12-year-old *Eucalyptus urophylla* wood clones, for the material used in calibration and cross-validation of the model for basic wood density.

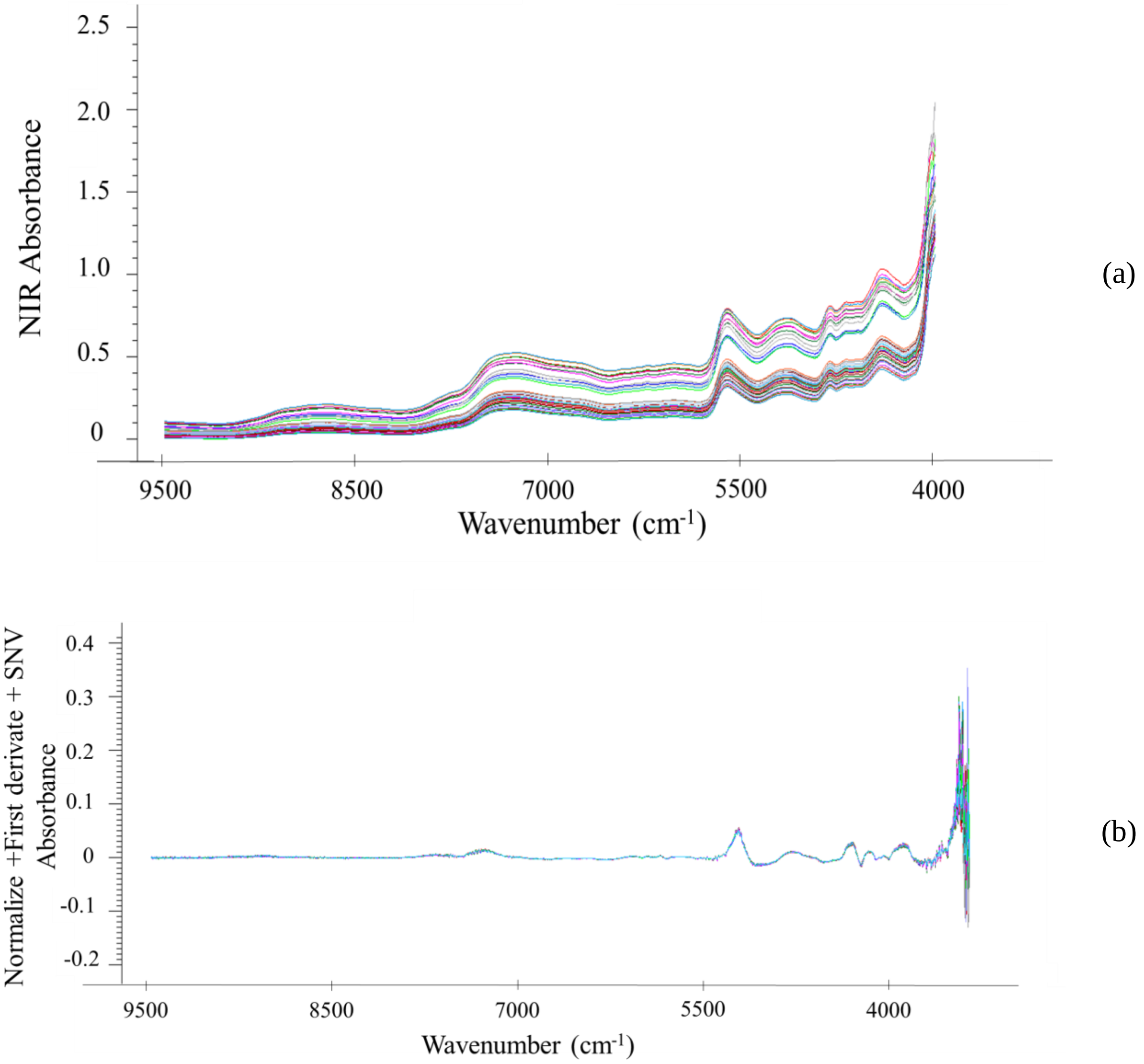
Figure 14 – (a) Diffuse reflection spectra obtained with original data and (b) with the treatment of the first derivative and SNV, for the wood basic density data.



Source: Personal (2017).

Figure 15a illustrates the untreated NIR spectra measured and 15b the NIR spectra treated with Normalize, First derivate and SNV of 12-year-old *Eucalyptus urophylla* wood clones, for the material used in calibration and cross-validation of the model for MOE.

Figure 15 – (a) Diffuse reflection spectra obtained with original data and (b) with the treatment of the normalize, first derivative and SNV, for the MOE data.



Source: Personal (2017).

The wave numbers of 9500 to 12000 cm^{-1} of the NIR spectra of the wood present a lot of noise, and it is difficult to obtain useful information for the analyzes and can be excluded. The spectral signature is a result of the interaction of light with the constituent molecules of the material, so each material presents a peculiar response to the incident radiation (PASQUINI, 2003). Usually, spectral information has noises or imperfections, so mathematical treatments are used to minimize this problem. Martens and Tormod (1989) argue that mathematical treatments aim to improve signal quality and reduce noise.

4.1.1 NIRS – based calibrations and validations

Calibrations and validations (cross-validation and external validation) were performed based on the spectral signatures of the wood samples to estimate ρ and MOE. The statistics associated to the Partial least square (PLS-R) regressions developed for correlating variations in NIR spectra to the laboratory-determined values of ρ and MOE are listed in Table 7.

Table 7- NIR models for estimating wood basic density (ρ, kg m^{-3}), Modulus of Elasticity (MOE, MPa) in 12-years-old *Eucalyptus* wood.

Trait.	Treat.	R^2_{cv}	RMSECV	R^2_p	RMSEP	RPD	LV	Outliers (%)
P	Snv+1st der.	0.72	37.00	0.73	35.00	1.97	8	3.53
MOE	Norm.+ Snv+1st der.	0.70	1024	0.79	843	1.99	8	3.11

Treat mathematical treatment of NIR spectra, *Snv* Standard Normal Variate correction, *1st der* first derivative transformation, R^2p coefficient of determination of prediction (test-set validation), *RMSEP* the root means standard error of prediction (test-set validation), *LV* number of latent variables and *RPD* ratio of performance to deviation.

Source: Personal (2017).

Considering the promising model statistics ($R^2_{cv} \geq 0.70$), it can be said that the PLS-R models for ρ and MOE provided good coefficients of determination (R^2_{cv} = 0.72 and R^2_{cv} = 0.70, respectively), and good values of "performance ratio for deviation" (RPD = 1.97 and RPD = 1.99, respectively) for the properties analyzed.

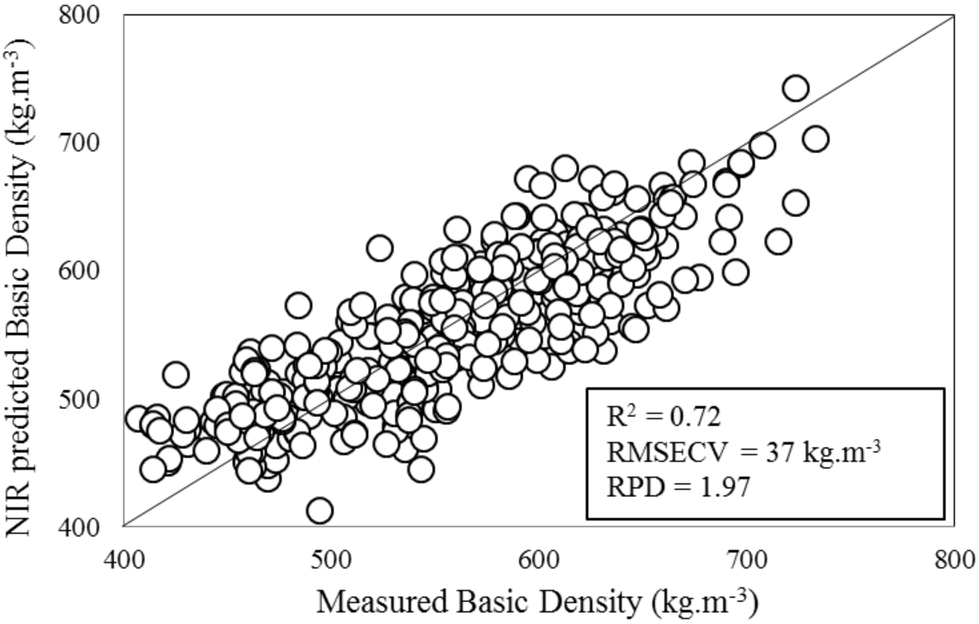
Gindl and Schoberl (2001) used Near Infrared Spectroscopy and applied the PLS regression to correlate the spectral data with density and MOE and found a correlation coefficient (R^2) of 0.98 and 0.96 respectively for the wood of the species *Larix decidua* Mill. Hein et al. (2009a) and Andrade et al. (2010), in two studies performed with *Eucalyptus*, found values of R^2 for the MOE of 0.79 and 0.78, respectively. Hein et al. (2012), also working with *Eucalyptus*, obtained an R^2 of 0.78 for the basic density of wood.

Considering the models generated for the prediction of the data for the ρ and MOE, the values of R^2 found were also considered satisfactory, being that for the ρ the R^2_{cv} was 0.73 and for the MOE was 0.79. Hein et al. (2009a), studying the same species of *Eucalyptus*, found a R^2_p for the basic density of 0.85 and Hein et al. (2010c), analyzing *E. grandis* and *E. urophylla*, found a R^2_p for the MOE of 0.68.

In relation to the Standard Deviation Relation (RPD), the values of 1.97 and 1.99 for ρ and MOE, respectively, were obtained. Schimleck et al. (2003) stated that for use in the field of forest sciences, values of RPD greater than 1.5 are considered satisfactory. In this way, the values obtained in this work are considered as good. According to Fujimoto et al. (2008), the higher the RPD index the more reliable is the model.

NIR-predicted versus laboratory-determined values plot for basic ρ and MOE of the wood are given in Figure 16 and Figure 17, respectively. These figures show the distribution of the validation points of the best models for the analyzed properties.

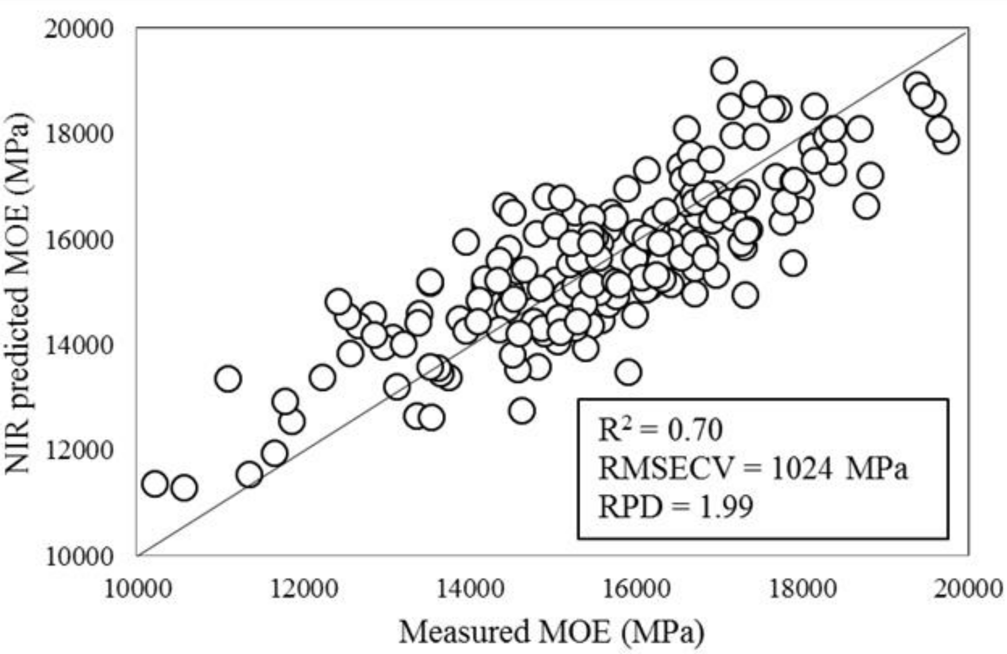
Figure 16 – NIR predicted versus measured values plot for basic density (kg.m^{-3}) of wood by cross-validation model.



Source: Personal (2017).

Figure 16 shows a strong association between the values measured and predicted by the model, indicating the possibility of using the NIRS technique to estimate the basic density of the wood (R^2_{cv}=0.72; RMSECV = 37 kg.m^{-3}).

Figure 17 – NIR predicted versus measured values plot for MOE (MPa) of wood by cross-validation model.



Source: Personal (2017).

Figure 17 shows a good association between the values measured and predicted by the model, indicating the possibility of using the NIRS technique also to estimate the MOE of the wood (R^2_{cv}=0.70; RMSECV = 1024 MPa).

4.2 SPATIAL VARIATION OF WOOD PROPERTIES

Table 8 shows the statistical summary of basic density and MOE analysis including the mean, minimum (Min) and maximum (Max) values of the results, and the coefficient of variation (CV) of wood of *Eucalyptus* clones in all three different plant spacing.

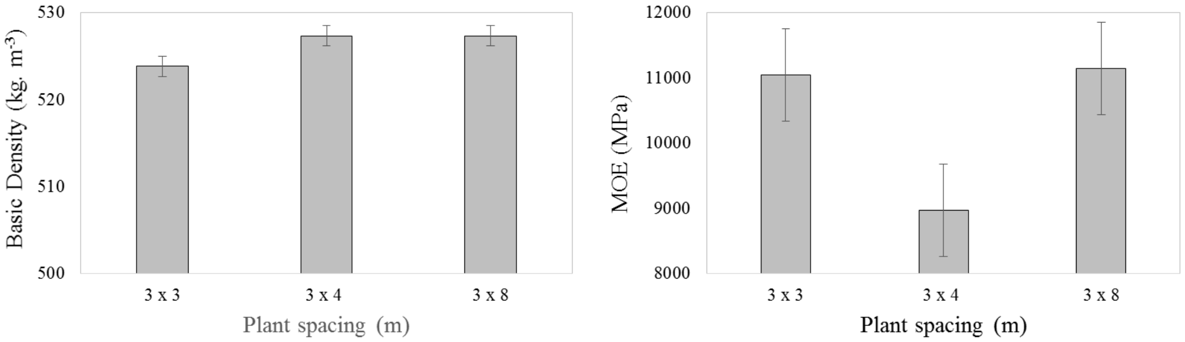
Table 8 - Descriptive statistics, including average, minimum (Min), maximum (Max), number of samples (N) and coefficient of variation (CV) for basic density (ρ, kg.m^{-3}) and Modulus of elasticity (MOE, MPa) measurements in four clones of 12-year-old *Eucalyptus urophylla* wood.

Plant spacing (m)		**Basic density**					**MOE**				
		i144	**2486**	**i182**	**GG100**	**Overall**	**i144**	**2486**	**i182**	**GG100**	**Overall**
3 x 3	**Average**	519.5	521.2	515.8	538.9	**523.8**	10813	10743	10355	12247	**11040**
	Min	438	437.5	459.7	480.3	**453.9**	7475	7550	7397	9038	**7865**
	Max	605.7	606.3	624	652.7	**622.2**	14659	14982	13338	16437	**14854**
	CV (%)	9.3	9.1	7.4	7.1	**8.2**	17.7	17.8	16.1	15.55	**17**
	N	198	198	198	198	**198**	198	198	198	198	**198**
3 x 4	**Average**	532.5	518.7	513.7	544.4	**527.3**	11534	1108	10716	12498	**8964**
	Min	477.3	447.7	439.3	483.2	**461.9**	8364	8193	7690	8615	**8216**
	Max	627.3	607.3	616	635.33	**621.5**	15558	14015	13724	16141	**14860**
	CV (%)	7.4	8.7	8.6	6.4	**7.8**	16.7	15.3	17.4	14.2	**16**
	N	198	198	198	198	**198**	198	198	198	198	**198**
3 x 8	**Average**	521.41	527.2	511.4	549	**527.3**	10601	11114	10478	12359	**11138**
	Min	441.8	450.7	433	488.5	**453.5**	7047	7839	7247	9332	**7866**
	Max	621.3	624.7	599.3	649.3	**623.7**	14393	14825	13528	16357	**14776**
	CV (%)	10.4	8.52	9.42	7.44	**8.9**	18.3	17.7	16.5	15.2	**17**
	N	198	198	198	198	**198**	198	198	198	198	**198**

Source: Personal (2017)

The basic density of the wood varied from 433 to 652.7 kg m^{-3} according to the site where they come from. The trees from the plant spacing 3 x 8, has the variation of the values of 453.5 to 623.7 kg m^{-3}, the 3 x 4 has 461.9 to 621.5 kg m^{-3}, and the 3 x 3 has 453.9 to 622.2 kg m^{-3}. The results are present at the Figure 18, and lead us to suppose that trees developing at higher growth rates tends to produce high wood densities while trees growing at high growth rates will result in low dense woods.

Figure 18– Mean and standard deviation values of basic density and MOE for the samples obtained in different plant spacing.

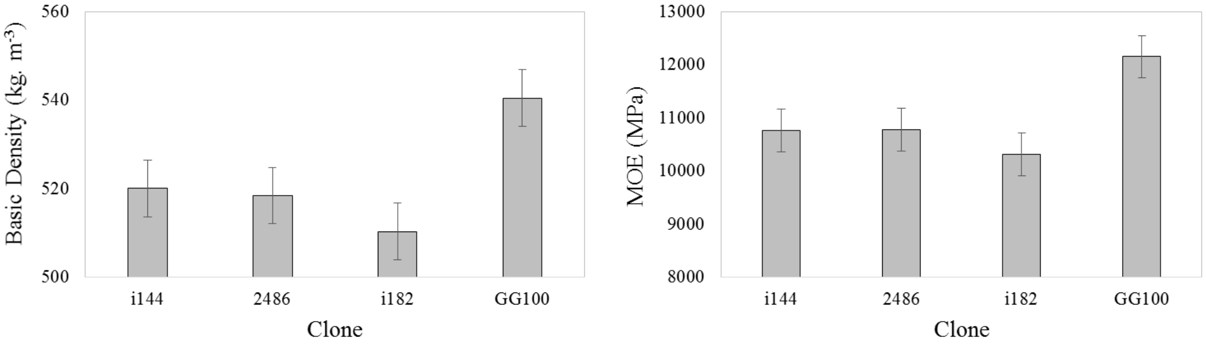


Source: Personal (2017).

The MOE varied from 7047 to 16437 MPa also according to the site where they come from. The trees from the plant spacing 3 x 8, has the variation of the values of 7047 to 16357 MPa, the 3 x 4 has 7690 to 16141 MPa , and the 3 x 3 has 7394 to 16437 MPa. The results are also present at the Figure 18 and shows that the MOE has a great correlation with the basic density of the wood.

When analyzing the different clones, the values for basic wood density range from 438 to 627.3 kg.m^{-3} for clone i144, 437.5 to 624.7 kg.m^{-3} for the clone 2486, 433 to 624 kg.m^{-3} for clone i182, and 480.3 to 652.7 kg.m^{-3} for GG100 clone. Regarding the MOE, for clone i144 the values range from 7047 to 15558 MPa, for 2486 from 7550 to 14982 MPa, for the i182 from 7247 to 13724 MPa and for the GG100 from 8615 to 16437 MPa (FIGURE 19).

Figure 19 – Mean and standard deviation values of basic density and MOE for the samples obtained in different genetic materials.



Source: Personal (2017).

4.2.1 Different plant spacing

The results show the spatial variation in wood Basic density (ρ) and stiffness (MOE) among the *Eucalyptus* trees planted by three different plant spacing. This spatial variation in wood traits over the entire trunk it is related to the growing conditions. Table 9 shows the radial variation of ρ and MOE along the tree height for all clones in the three different plant spacing.

Table 9 - Radial increase of values of wood properties (maximum value subtracted from the minimum value) and the percentage change value (between the parentheses), according to the tree height (in % of commercial height) and plant spacing.

Wood trait	**Plant spacing (m)**	**% of tree height**					
		0	**BH**	**25**	**50**	**75**	**100**
Basic density (kg m^{-3})	**3 x 3**	111.6abA (18.3%)	106.4aA (18.1%)	88.5aA (15.5%)	84.5abAB (14.9%)	89.5aA (16.2%)	18.0aB (3.7%)
	3 x 4	97.6 bA (16.9%)	99.8aA (16.9%)	97.7aA (17.1%)	72.5bA (12.8%)	65.2 aAB (11.7%)	23.2aB (4.7%)
	3 x 8	140.5aA (22.8%)	123.1aAB (20.6%)	106.3aAB (18.2%)	107.1aAB (18.5%)	86.0aB (15.3%)	27.1aC (5.5%)
MOE (MPa)	**3 x 3**	5292aA (42.7%)	5715aA (45.9%)	6023aA (47.7%)	5432aA (43.3%)	4081aB (32.5%)	1809aC (17.8%)
	3 x 4	4949aAB (42.5%)	5450aA (40.1%)	5861aA (46.7%)	4601aAB (42.1%)	3224aBC (31.2%)	2316aC (28.9%)
	3 x 8	5814aAB (48.2%)	5801aAB (47.7%)	6130aA (39.1%)	5360aAB (43.1%)	4555aB (37.5%)	2061aC (25.6%)

Means followed by the same capital letters between positions (same treatment) and the same lower case between treatments (same position) do not differ to 5% of significance by the Tukey test.
Source: Personal (2017).

Considering the values of the basic density between the three plant spacing's analyzed, it can be observed that in 0% and 50% of the height of the tree, the highest values were obtained at 3 x 8 meters, which did not differ statistically from 3 x 3 meters, and the lowest values were found in 3 x 4 meters, which also did not differ statistically from the 3 x 3 meters. At heights BH, 25%, 75% and 100%, there was no difference between the plant spacing's analyzed.

Therefore, the effect of plant spacing on the basic density of the wood, was only present in heights 0 and 50% of the tree.

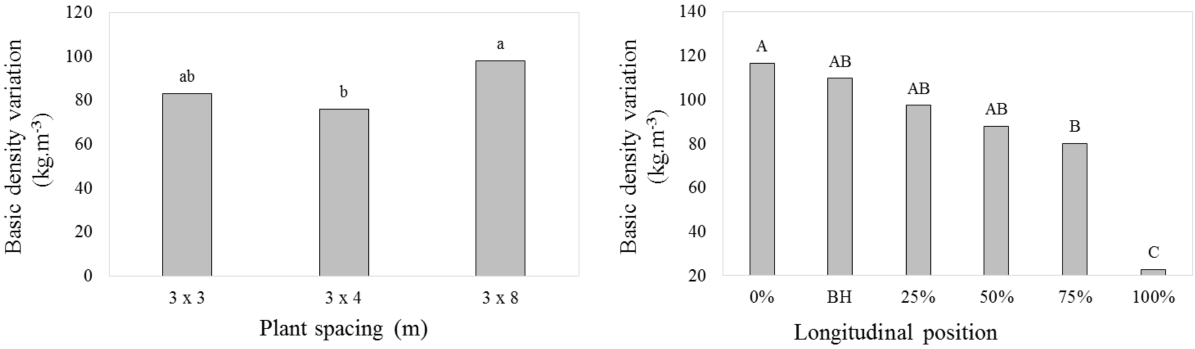
Considering the variation of the basic density along the trunk, within the plant spacing, for all the plant spacing's, the highest values were found in the 0%, where statistical differences were not obtained up to 50% of the tree. The lowest values were obtained at 100% height.

For the basic density, at the 0%, it is observed that the higher radial variation occurs at the plant spacing 3 x 8 m, highlighting a smaller variation observed in the spacing 3 x 4. However, there was no statistically significant difference in the values of density variation in the pith-to-bark direction as a function of the plant spacing, for all the heights analyzed.

Although not statistically different, the larger variations of this property occurred on the disc obtained at the 0%. This greater variation of the values of the basic density of the wood at base was already expected since there are formed in all the twelve years of the tree. In the 0% position, all tree growth rings are present since the number of annual growth rings decreases from the base towards the top of the trunk, and the variations in fiber dimensions follow the same model of variation (SANTOS; NOGUEIRA, 1974).

Considering the overall average of the three plant spacing, at different heights, the basic density variations in the pith-to-bark direction were more accentuated at 0% of the height and the lowest variation occurred at 100% of the commercial height (FIGURE 20).

Figure 20 – Overall average of the relative radial increase of the Basic density between the different plant spacing and different longitudinal positions.



Source: Personal (2017).

According with Downes et al. (2009), if wood property variation from pith-to-bark is a function of changing environmental and physiological conditions, it expected that there would be a great relationship between growth rate and wood properties.

It is observed a general tendency of the lower values of the basic density of the wood to occur in the region of the marrow, increasing until near the region of the sapwood causing a reduction of its value.

As observed in this study, Oliveira et al. (2005), analyzing wood from *E. citriodora*, found the lowest variation of the values of the basic density in the BH, indicating the formation of the wood more uniform and appropriate for the wide range of use.

Several factors influence the growth rate of the tree, with for example silvicultural treatments. Different trees can exhibit the same daily stem growth increment (growth rate), but have different patterns of growth within that day. One tree may spend more hours per day in growth, but have a slower rate of cell division or expansion in contrast to another, which spends fewer hours per day in the increment phase but produces that increment at a faster rate (DOWNES et al. 1999).

In *Eucalyptus*, the increase in the basic density of wood varies with age, with a tendency to stabilize after the formation of adult wood. There is therefore a need to determine the age of the trees for comparison, as well as the conditions of the site (RIBEIRO; ZANI FILHO, 1993).

The global increase from base to top in wood basic density was observed on the three plants spacing analyzed.

For the plant spacing 3 x 3 meters it was observed that the variation of the basic density, in the pith-to-bark direction, on the 0% was 116.6 kg.m^{-3} and top was 18 kg.m^{-3} with an overall average, along the trunk of 83.1 kg.m^{-3}. On the plant spacing 3 x 4 meters, the values were 97.6 and 23.2 kg.m^{-3} base and top respectively, with an overall average of 76 kg.m^{-3}, and on the plant spacing 3 x 8 meters, 140.5 and 27.1 kg.m^{-3} base and top, with an overall average of 98.1 kg.m^{-3}. That indicates that the higher overall average of the longitudinal variation of wood density occurs at the plant spacing 3 x 8 m. However, this average does not differ statistically from that found in the plant spacing 3 x 3, which also did not differ statistically from the average obtained in the plant spacing 3 x 4 m (FIGURE 20).

Variation of wood density with plant spacing is still a controversial issue. Medhurst et al. (2012) stated that the impact of reduced competition and increased diameter growth rate on the properties of eucalypt wood is not well defined or understood.

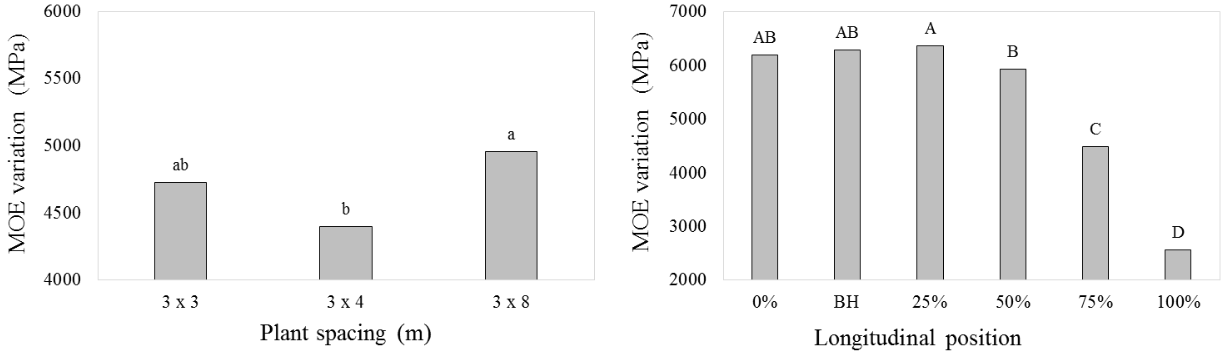
The formation of wood is a biological process that occurs within the living tree and the quality of the wood can only be altered through this process. Until a certain extent, factors related to wood quality can be modified, controlled, minimized or improved through silvicultural treatments and genetic selection and breeding (ZOBEL, 1981).

For wood stiffness values, the same tendencies were also observed, that is, there was no significant statistical difference of the pith-to-bark variation of the MOE values at the different heights analyzed, depending on the plant spacing.

Considering the MOE values found in Table 9, it was observed that there was no statistical difference between the plant spacing's analyzed, in the different positions. Among the different positions along the trunk, the same tendency of the basic density was observed, with values being 100% lower and in the base, up to 50%, there was no significant statistical difference.

For the plant spacing 3 x 3 meters it was observed that the variation of the MOE, in the pith-to-bark direction, on the 0% was 5292 MPa and top was 1809 MPa with an overall average, along the trunk of 4725 MPa. On the plant spacing 3 x 4 meters, the values were 4949 and 2316 MPa base and top respectively, with an overall average of 4400 MPa, and on the plant spacing 3 x 8 meters, 5814 and 2061 MPa base and top, with an overall average of 4954 MPa. That indicates that the higher overall average of the longitudinal variation of MOE occurs also at the plant spacing 3 x 8 m (FIGURE 21). However, this average does not differ statistically from that found in the plant spacing 3 x 3, which also did not differ statistically from the average obtained in the plant spacing 3 x 4 m.

Figure 21 – Overall average of the radial increase of the MOE between the different plant spacing and different longitudinal positions.



Source: Personal (2017).

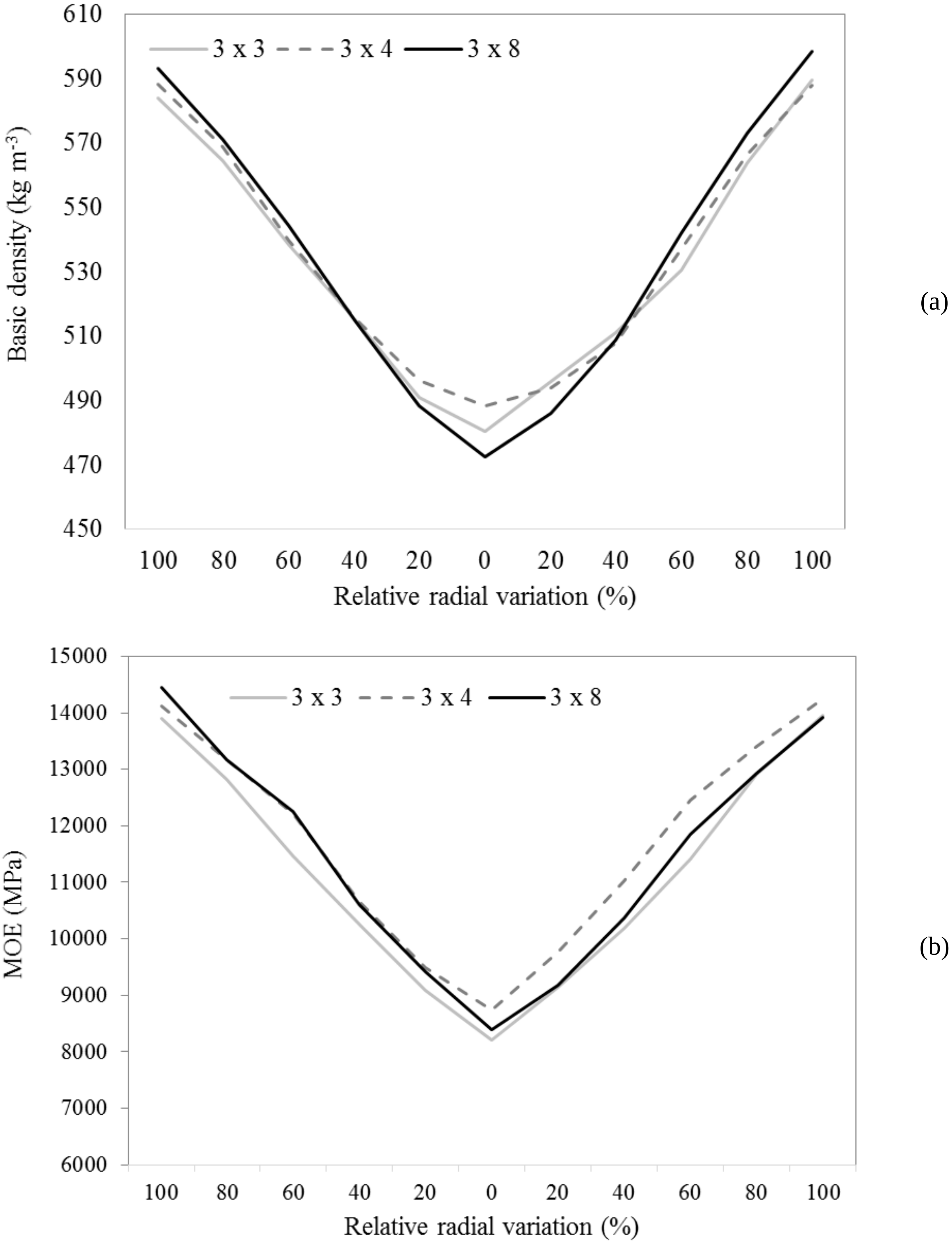
The same tendency was observed by Hein et al. (2016), in which they worked with 6-years-old *Eucalyptus grandis* x *E. urophylla* hybrids growing in three contrasting clonal tests in Brazil.

Considering the overall average of the three plant spacing, at different heights, the MOE variations in the pith-to-bark direction were more accentuated at 50% of the height, being that at 0% and BH did not differ statistically from that, and the lowest variation occurred at 100% of the commercial height (FIGURE 21).

Evans et al. (2000a), mention that the mechanical properties of wood are mainly dependent on the basic density, juvenile wood percentage, insect attack intensity and presence of knots. According to Cave and Walker (1994), the great difference in strength and stiffness between adult and juvenile wood does not occur exclusively due to differences in density, with the highest Microfibril angle (MFA) of juvenile wood tracheids being responsible for these properties. MFA declines from pith to bark but, unlike conifers, the angles are much lower near the pith (DONALDSON, 2008).

The Figure 22 shows the radial variation of the basic density and wood stiffness of the *Eucalyptus* trees at the diameter at breast height (BH) in the three different plant spacing.

FIGURE 22 – Relative radial variation of basic density (kg m^{-3}) (a) and modulus of elasticity (MOE) (MPa) (b) in *Eucalyptus* clones at BH.



Source: Personal (2017).

The variations in wood density and stiffness, considering pith to bark direction, at BH, can be observed at the Figure 22, but, overall, the properties strongly varied from pith to the bark always presenting lower values for this property near the pith.

The values of the basic density decreased, at mean, 18.1%, 17% and 20.7% in the plant spacing of 3 x 3, 3 x 4 and 3 x 8 meters, respectively. Regarding the values for the MOE, those decreased, at mean, 41%, 38.4% and 40.9% in the plant spacing of 3 x 3, 3 x 4 and 3 x 8 meters, respectively.

Faster growth population, considering changes in growth conditions in conifers and hardwoods, can cause both decrease or increase in fiber length, apparent wood density and strength, and increase its gradient in the direction pith to bark (LIMA; GARCIA, 2011).

All those variations on the properties of the wood, radial and longitudinally, can be explained by the characteristic of the high-density plantations, the time required for canopy closure, which is shorter as compared to low-density stands, and this affects both growth increments and their pattern of variation (ISHIGURI et al. 2005). Normally, at the first years, the growth of trees is faster and then it declines. This happened due to the canopy closure and the increased competition among trees (DEBELL et al. 2004). At smaller spacing stands, leaf area and biomass develop more rapidly and the site is “fully occupied” sooner. Early stand growth rates will be faster at smaller spacing and the current peak or mean annual increments can occur sooner (STAPE; BINKLEY, 2010; CHEN et al., 2011).

The tendency observed in the Table 9 and Figure 22 also was found by Downes et al. (2014), analyzing the wood properties of 10-years-old trees in *Eucalyptus globulus* plantations, at different three sites (unthinned, 1250 stems ha^{-1}; thinned to 600 ha^{-1} or 300 stems ha^{-1}), and nitrogen fertilizer application (250 kg ha^{-1} elemental nitrogen and control). They concluded that the air-dry wood density and MOE all increased, on average, from pith to bark. The pith-to-bark trends of increasing of both density and stiffness properties reported here are consistent with those found in other studies on eucalypts (MEDHURST et al., 2012, WENTZEL-VIETHEER et al., 2013).

Malimbwi et al. (1992) have analyzed the effect of the plant spacing at *Cupressus lusitanica* at the age of 19 years and concluded that basic density, heartwood content, modulus of elasticity, modulus of rupture and compression parallel to grain were not significantly affected by plant spacing. The same tendency was found by Ishiguri et al. (2005), who investigated the effect of the plant spacing in the wood basic density, the length of latewood tracheids, and the microfibril angle of the S_2 layer of *Cryptomeria japonica* D. Don. at the age of 35 years old.

4.2.2 Different genetic materials

The results show the spatial variation in wood basic density (ρ) and stiffness (MOE) along the trunk of four genetic materials of *Eucalyptus* trees. This spatial variation in wood traits over the entire trunk it is related to the growing conditions. Table 10 shows the radial variation of ρ and MOE along the tree height for all clones.

Table 10 - Radial increase of values of wood properties (maximum value subtracted from the minimum value) and the percentage change value (between the parentheses), according to the tree height (in % of commercial height) and genetic material.

Wood trait	**Clones**	**% of tree height**					
		0	**BH**	**25**	**50**	**75**	**100**
Basic density (kg m^{-3})	**i144**	124.7aA (20.4%)	120.8aA (20.4%)	122.8aA (20.7%)	100.6aA (17.3%)	101.9aA (18.1%)	20.3aB (4.1%)
	2486	100.6aA (16.6%)	117.2aA (19.9%)	119.8abA (20.6%)	88.5aAB (15.4%)	105.7aA (18.6%)	19.2aB (3.9%)
	i182	115.5aA (19.5%)	103.4aAB (17.8%)	69.9bBC (12.7%)	82.0aABC (14.7%)	45.8aCD (8.7%)	15.7aD (3.3%)
	GG100	125.5aA (19.8%)	97.61aAB (16.2%)	77.6abBC (13.3%)	81.1aABC (14.1%)	67.4aBC (11.9%)	33.8aC (6.5%)
MOE (MPa)	**i144**	5481aAB (39.7%)	5791aAB (41.9%)	6740aA (46.8%)	5515aAB (38.9%)	4711aB (34.8%)	2039aC (19.7%)
	2486	5035aAB (37.3%)	5294aA (38.7%)	5937aA (41.9%)	5121aA (37.5%)	4014aAB (31.1%)	2117aB (20.2%)
	i182	5309aA (40.7%)	5480aA (41.2%)	5308aA (40%)	4791aAB (37.7%)	3763aB (29.9%)	1732aC (17.8%)
	GG100	5585aA (36.3%)	6057aA (38.8%)	6037aA (39%)	5100aA (34.3%)	3327aB (23.4%)	2361aB (20.2%)

Means followed by the same capital letters between positions (same treatment) and the same lower case between treatments (same position) do not differ to 5% of significance by the Tukey test.
Source: Personal (2017).

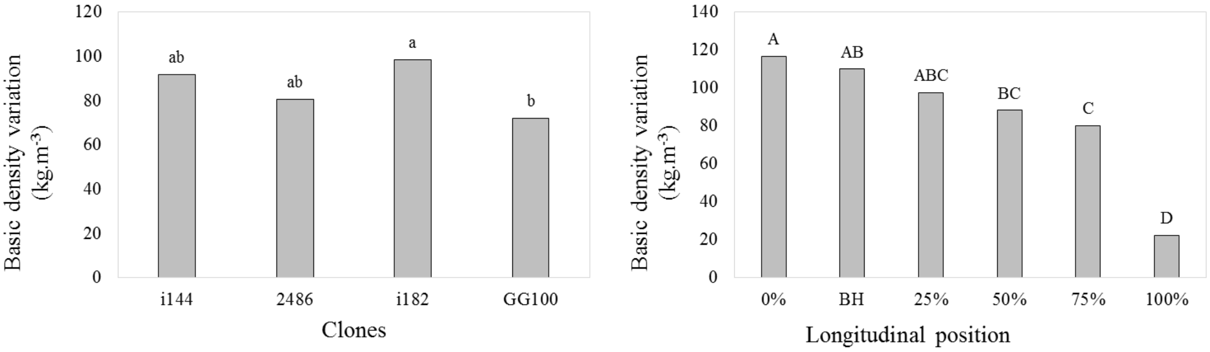
Considering the values of the basic density for the four clones analyzed, it was observed that there was no significant difference between the values as a function of the clones, practically throughout the tree. At the height 25%, clone i182 presented inferior results to the other clones, for this property.

Analyzing the density values at the different positions along the tree, for clones i144 and 2486, the highest values were found at the base. These values do not show statistical difference up to 75% of the trees, and the lowest values were obtained at 100% height. For clones i182 and GG100, the highest values were also found at 0% and BH, where there was no statistical difference, and the lowest values were also obtained at 100%.

For the basic density, at the 0%, it is observed that the higher radial variation occurs at the GG100 clone, highlighting a smaller variation observed in the i182. However, there was no statistically significant difference in the values of density variation in the pith-to-bark direction as a function of the genetic material, for all the heights analyzed.

Considering the overall average of the four clones analyzed, at different heights, the basic density variations in the pith-to-bark direction were more accentuated at 0% of the height and the lowest variation occurred at 100% of the commercial height, showing a decrease of the average overall values of base-to-top variation of 80.9% (FIGURE 23).

Figure 23 – Overall average of the radial increase of the Basic density between the different clones and different longitudinal positions.



Source: Personal (2017).

Sotelo Montes and Weber (2009) found there was significant variation in wood density due to provenances in *Prosopis africana* at 13 years-old. The influence of the genetic variation in wood density due to provenances has also been reported in other tropical hardwood species, Arnold et al. (2004), Santos et al. (2004) and Sotelo Montes et al. (2006).

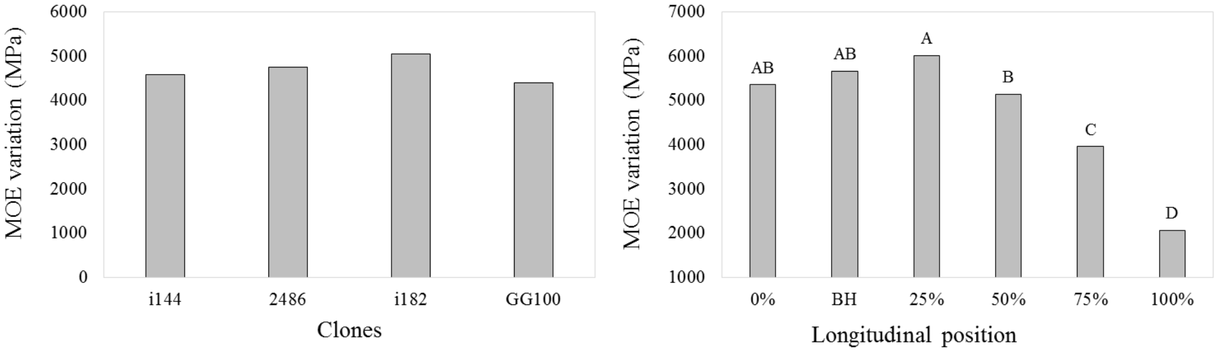
Some wood properties, like basic density of tropical hardwoods, typically shows higher heritability than growth traits. That tendency can be observed in studies like, for example, Raymond (2002) and Sotelo Montes et al. (2006). Wood density and other wood properties tend to be under stronger genetic control than growth traits (ZOBEL; JETT, 1995).

Figure 23 show that, for the clone i144 it was observed that the variation of the basic density, in the pith-to-bark direction, on the 0% was 124.7 kg.m^{-3} and top was 20.3 kg.m^{-3} with an overall average, along the trunk of 91.8 kg.m^{-3}. On the clone 2486, the values were 100.6 and 19.2 kg.m^{-3} base and top respectively, with an overall average of 80.5 kg.m^{-3}, on the i182, 115.5 and 15.7 kg.m^{-3} base and top, with an overall average of 98.5 kg.m^{-3} and on the GG100, 125.5 and 33.8 kg.m^{-3} base and top, with an overall average of 72.1 kg.m^{-3}. That indicates that the higher overall average of the longitudinal variation of wood density occurs at the clone i182. However, this average does not differ statistically from that found in the clones i144 and 2486, which also did not differ statistically from the average obtained in the clone GG100, that shows the smaller variation.

In relation to the pith-to-bark variation, the same tendency is observed. The greatest variation of the basic density occurs in the disks obtained at the 0% height, while the lowest variation occurs at 100% of the total height.

In Table 10, observing the MOE values, no significant statistical differences were found among the four clones analyzed. In relation to the different positions along the tree, it can be observed that the MOE presented the same trend observed for the basic density, with the lowest values being 100%. At 0%, 25% and 50% heights, no significant statistical differences were observed.

Figure 24 – Overall average of the radial increase of the MOE between the different clones and different longitudinal positions.



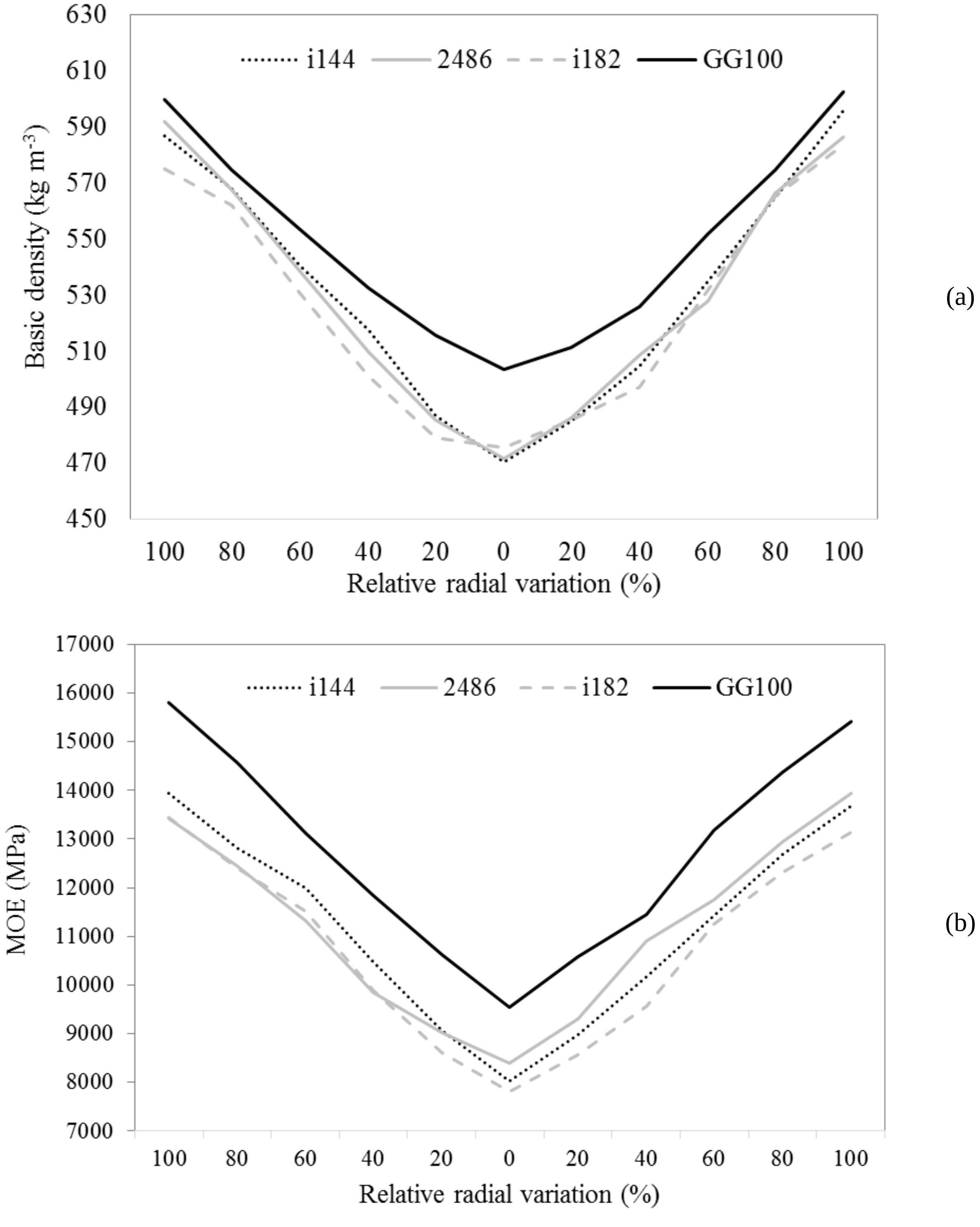
Source: Personal (2017).

For wood stiffness values, the same tendencies were also observed, that is, there was no significant statistical difference of the pith-to-bark variation of the MOE values at the different heights analyzed, depending on the genetic material.

For the clone i144 it was observed that the variation of the basic density, in the pith-to-bark direction, on the 0% was 5481 and top 2039 MPa, with an overall average, along the trunk of 4586 MPa. On the clone 2486, the values were 5035 and 2117 MPa base and top respectively, with an overall average of 4744 MPa, on the i182, 5309 and 1732 MPa base and top, with an overall average of 5046 MPa, and on the GG100, 5585 and 2361 MPa base and top, with an overall average of 4397 MPa. It was observed, in this case, that the values of the general mean of the MOE, in relation to the clones analyzed, did not present significant statistical difference (FIGURE 24). However, considering the pith-to-bark variation, the greatest variation of the basic density occurs in the disks obtained at the 25% height, which does not differ statistically from those obtained at heights 0% and BH, while the lowest variation occurs at 100% of the total height.

The Figure 25 shows the radial variation of the basic density and wood stiffness of the *Eucalyptus* trees at the diameter at breast height (BH) in the different genetic materials.

FIGURE 25 – Relative radial variation of basic density (kg m^{-3}) (a) and modulus of elasticity (MOE) (MPa) (b) in *Eucalyptus* clones at BH.



Source: Personal (2017).

The variations in wood density and stiffness, from different *Eucalyptus* clones, considering pith to bark direction, at BH, are observed at the Figure 25, where show smaller values near to the pith and higher near to the bark. Gonçalves et al. (2010) also found this same tendency of variation.

The values of the basic density decreased, at mean, 20.4%, 19.9%, 17.8% and 16.2% for the clones i144, 2486, i182 and GG100, respectively. Regarding the values for the MOE, those decreased, at mean, 41.9%, 38.7%, 41.2% and 38.8% for the clones i144, 2486, i182 and GG100, respectively.

It can be observed in Figure 25 that the same tendency of the radial variation to the BH was observed in all four clones analyzed, but the clone GG100 stands out because it presents a range of values a little higher than the others.

The variation of the properties of the wood is probably related to a tendency to stabilize the wood after the formation of adult wood, and also to the smaller percentages of juvenile wood, which is higher in the highest height (RIBEIRO; ZANI FILHO, 1993). According to Zobel (1981), the adult wood has very different characteristics from those presented in juvenile wood.

The variations of these properties of the wood, both radial and longitudinally, as a function of planting spacing, can be observed in the Figures 26 and 28.

4.2.3 Spatial variation of wood basic density

In the present study, the hypothesis is that the raising of wood basic density values, considering pith-to-bark direction, vary according to the plant spacing.

Our sampling indicates that the higher the plant spacing between the trees, the greater the magnitude of radial variation of wood density in all trunk. At the top of the trunk, there was no effect of plant spacing. Figure 26 presents the spatial variation of the wood density inside the trunk emphasizing the radial variation of the trees at 25 % and 75% of the trees height, and shows that trees produce denser wood at the site where the plant spacing between the trees was larger.

The radial variation is more consistent than the longitudinal variation. The variation of the properties at the top always is smaller since the wood produced has a younger age. Zobel and Van Buijtenen (1989) have affirmed that occurs significant effect of initial planting density over tree growth and, hence over wood quality. In addition, many studies have shown that the environment controls one part of the wood variation. The present study shows the effects of initial planting densities on tree growth features, wood density, and stiffness in *Eucalyptus* clones wood.

In particular, trees grew faster at larger plant spacing in terms of radial growth. The larger plant spacing between the trees tends to effectively capture more sunlight and absorb sufficient water and nutrients contributing for fast growth rates (NAJI; SAHRI, 2012). Some studies, as Rocha et al. (2016), working with *Eucalyptus grandis* x *E. camaldulensis*, found that wider plant spacing tends to produce trees with denser woods. Lim and Fujiwara (1997) also reported that wood density in rubberwood increased as planting density increased. In other study, Watson et al. (2003) have analyzed a 38-years-old coastal western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) finding that the wood density is not affected by plant spacing.

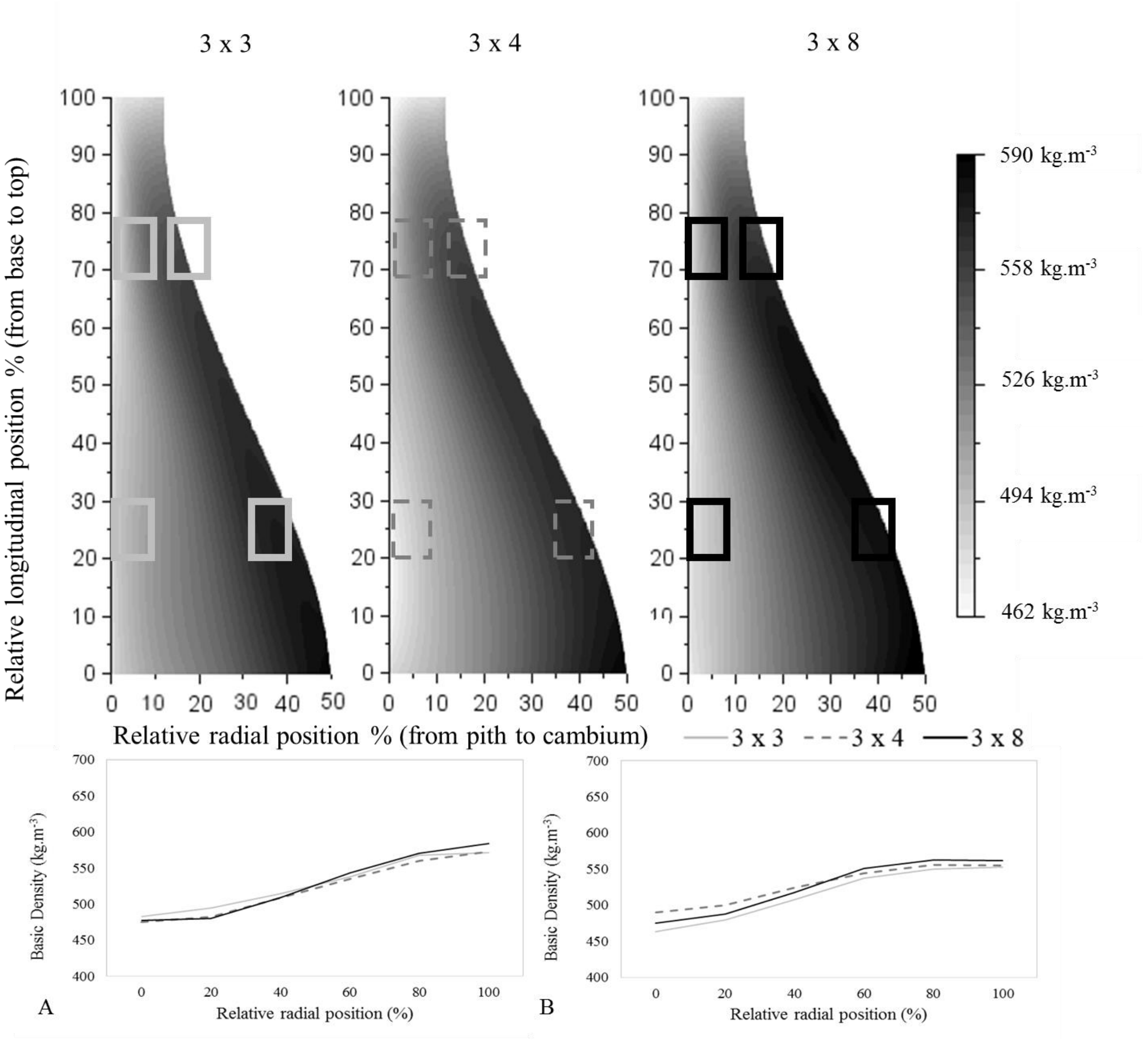
The spatial variation of the overall average of the basic density by different plant spacing can be seen in Figure 26.

Polli et al. (2006) observed in clones of *E. grandis* that wood density increased significantly in the pith-to-bark direction and decreased in the base-top direction.

Zobel et al. (1989), says that the species that shows a great difference of some wood properties between juvenile and mature wood, it is automatic that a variation with height will be observed for these properties due to the variation with height of the proportion of juvenile wood, which increases from the base to the top of the tree. The vertical variations of wood properties are less studied than the radial variations because data are much more complicated.

Bernardo et al. (1998) states that there is a variable behavior of the trees in relation to the spacing between the plants. They said that the changes in amounts of material allocated to different plant parts are a function of the plant, and when the trees are planted at increased spacing levels, will respond by allocating more proportional growth to root systems and foliage, thereby reducing the amount of material allocated to large woody structures. The stagnation of tree growth starts earlier in smaller plant spacing, as growth is substantially affected by that (LEITE et al., 2006).

FIGURE 26 - Relative spatial variation of wood basic density (kg m^{-3}) in *Eucalyptus urophylla* clones, highlighting the radial variation at 25 (A) and 75 % (B) of the tree height. Top mean value of all the studied clones.



Source: Personal (2017).

At reduced plant spacing, growth resources are limited, especially in younger plantations, when demand is high, imposing a reduction in growth rates (NETO et al. 2010).

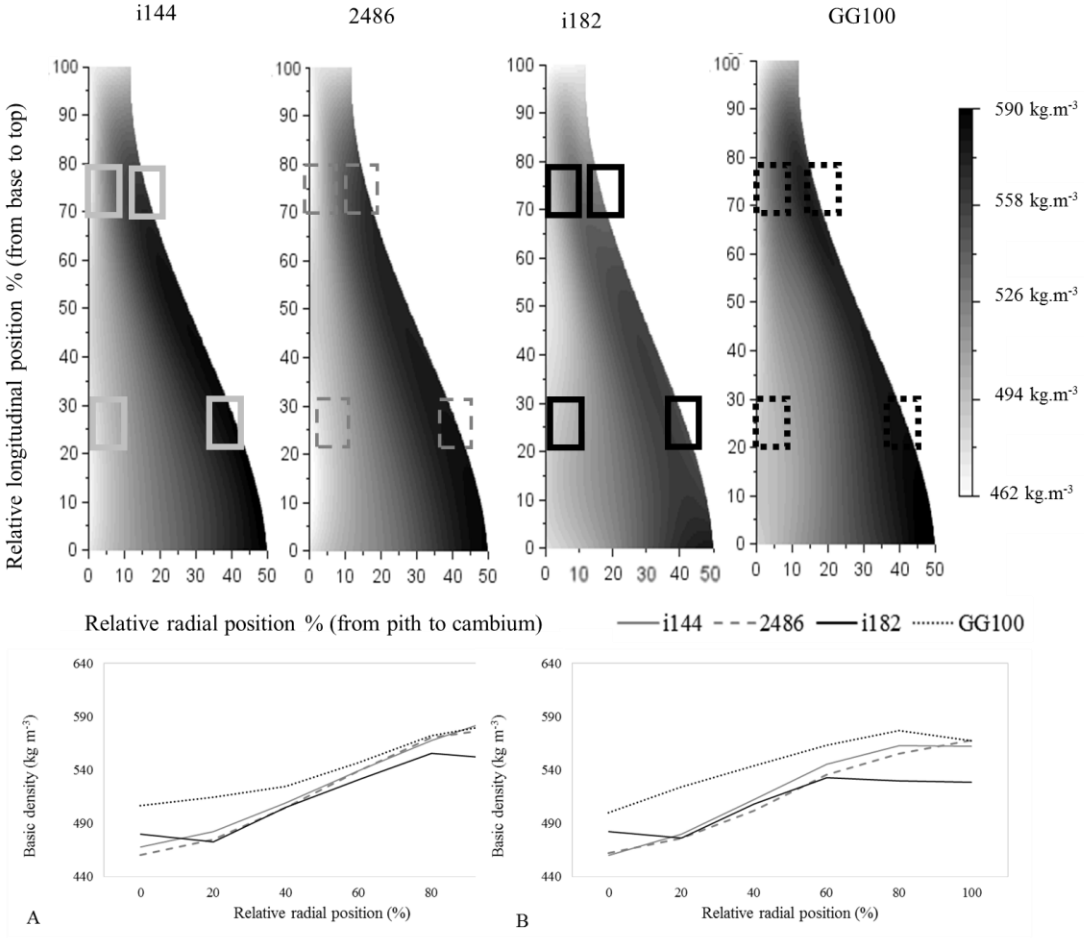
Thus, it is observed in Figure 26 that the greatest variation of the basic density of wood occurs in trees planted in the largest spacing, that is, 3 x 8 meters.

The higher overall average of the longitudinal variation of wood density occurs at the clone i182 and the smaller variation at the clone GG100. This behavior of the spatial variation shows that each clone can present specific characteristics, regardless of the location and the silvicultural conditions in which they are submitted.

In relation to the pith-to-bark variation, the same tendency is observed at 25 and 75% of the tree height. The greatest variation of the basic density occurs in the disks obtained at the clone i182, where we can easily see at the two graphics below the maps at the Figure 27.

Rodrigues et al. (2008), analyzing the effect of different clones on the physical properties of the wood, among them the basic density, found that the variations among the clones were significant for all the characteristics studied.

FIGURE 27 - Relative spatial variation of wood basic density (kg m^{-3}) in four *Eucalyptus urophylla* clones, highlighting the radial variation at 25 (A) and 75 % (B) of the tree height. Top mean value of all the studied clones.



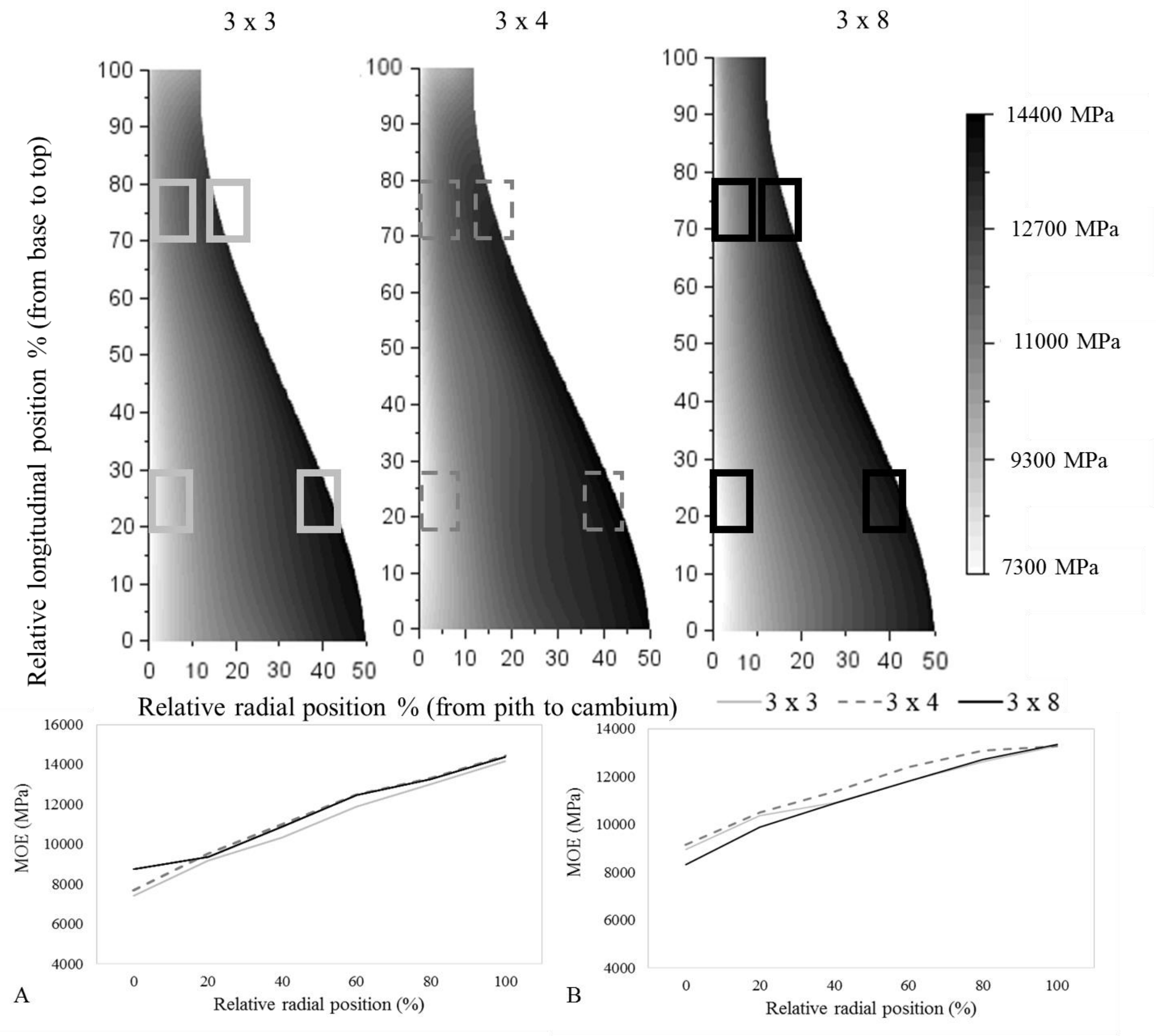
Source: Personal (2017).

In this way, it can be said that the genetic material also exerts influence on the behavior of the trees to the growth conditions in which they are submitted. This behavior mainly reflects the basic density of wood. Rodrigues et al. (2008) state that one of the attributes of quality most used in the various sectors of the industrial timber production is the basic density, since it is one of the most important properties of the wood, being considered a quality index that indicates the final use of the wood.

4.2.4 Spatial variation of wood Stiffness

Figure 28 shows the spatial variation of the overall average of the MOE by different plant spacing and highlights the radial values at 25 % and 75% of the tree height.

FIGURE 28 - Relative spatial variation of Modulus of Elasticity (MOE) (MPa) in *Eucalyptus urophylla* clones, highlighting the radial variation at 25 (A) and 75 % (B) of the tree height. Top mean value of all the studied clones.



Source: Personal (2017).

The patterns of variation in MOE and basic density were similar when considering overall values. On the wider plant spacing were found the higher variation of the stiffness, and the radial variation in MOE was higher on the bottom than those at the top of the trees. The spatial variation trends for MOE were similar than those for basic density when the plant spacing between the trees was considered in the analysis. However, the radial increase of MOE was significantly higher in trees grown in the plant spacing of 3 x 8 meters.

Hein et al. (2016) affirm that the high variation is caused by a shape effect. When a clamped beam with a conical shape is bending, the stress is maximum near the clamped end, thus, the tree produces wood with a maximum stiffness at this local to limit the deformation in this critical region.

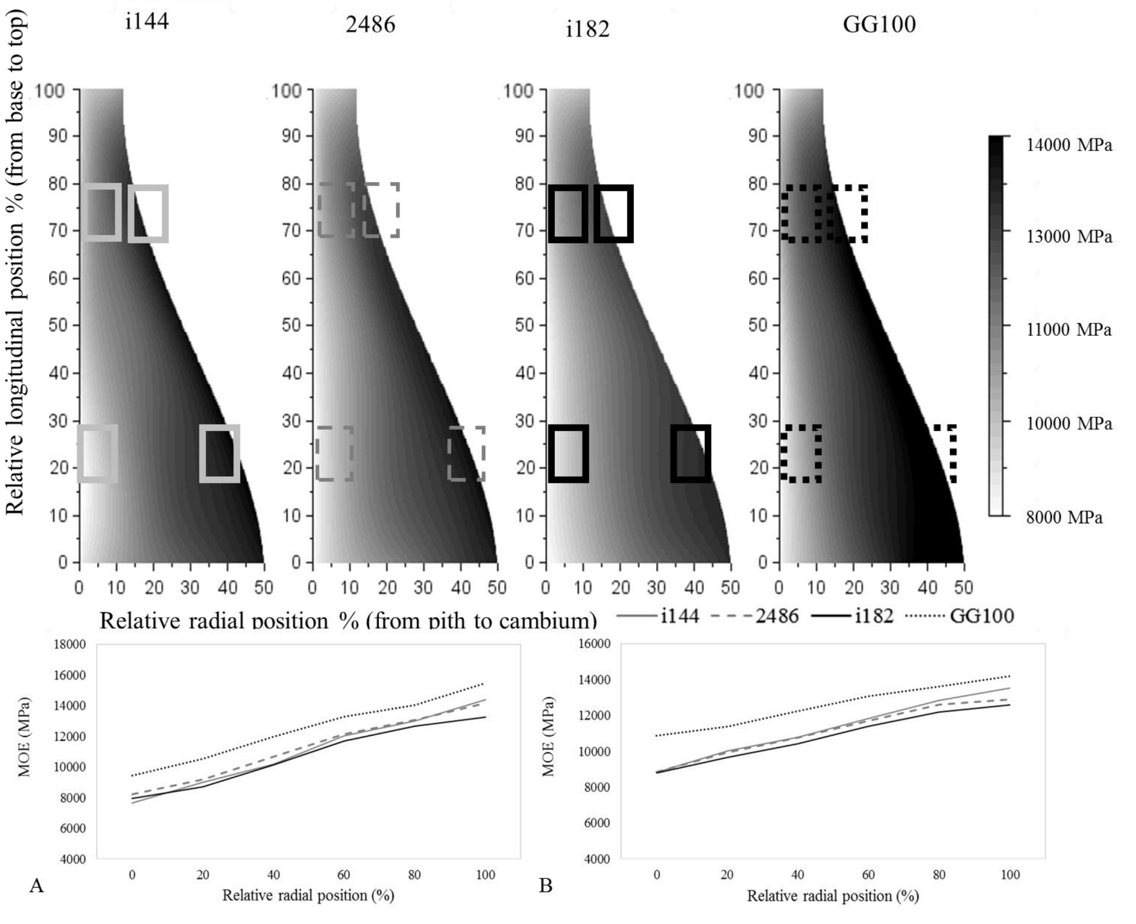
It is known that the wood stiffness is related to wood density (EVANS et al. 2000a) and wood stiffness increases as density increases (YANG; EVANS, 2003). Thus, according to Hein et al. (2016) the search for the knowledge about the factor that drives spatial variation in modulus of elasticity can be potentially interesting for sawmill timber producers.

In relation to the MOE, the different clones did not show different behavior in the spatial variation of this property, even if it was strongly influenced by the basic density of the wood, which in this study showed a variation depending on the genetic material.

In Figure 29, associated with the Table 10, it is possible to observe the behavior of the spatial variation in the four clones analyzed can be clearly observed, emphasizing the graphs at 25 and 75% of the height that show that all the clones had the same tendency of variation.

The spatial variation trends for MOE were different than those for basic density what can indicate that the tree growing site was taken into account. Breeding programmes have instead focussed on improving growth, form and tolerance of a wide range of site conditions (ZOBEL and JETT, 1995).

FIGURE 29 - Relative spatial variation of Modulus of Elasticity (MOE) (MPa) in four *Eucalyptus urophylla* clones, highlighting the radial variation at 25 (A) and 75 % (B) of the tree height. Top mean value of all the studied clones.



Source: Personal (2017).

5 CONCLUSION

In the wider plant spacing between the trees occurs the greater magnitude of longitudinal and radial variation in wood density, especially around the 0%, and for MOE, the greater magnitude is on the 25% of the tree height, which did not differ statistically at 0% and BH.

Considering the spatial variation of the wood properties, the study shows that the clones produce higher variation, for basic density and for stiffness, at the plant spacing of 3 x 8 meters. Trees growing under widely plant spacing present bigger diameter and higher variation on the basic density and MOE of the wood. The presented spatial variation along the trunks indicates that trees are able to adapt their wood to the changing environmental conditions, such as the availability of sunlight, nutrients and individual growth area, defined by the plant spacing.

The radial increase in the basic density in the 0 and 50% heights of trees planted at 3 x 4 m (97.6 and 72.5 kg.m^{-3}, respectively) was significantly lower than those planted at 3 x 8 m (140.5 and107.1 kg.m^{-3}, respectively). The results showed that there was an effect of the plant spacing on the radial variation of wood density at heights 0 and 50%.

In relation to the effect of the genetic material on the basic density of wood, it was observed that only at 25% height values were statistically different, with the highest values observed in clone i144 (122.8 kg.m^{-3}) lower values in clone i182 (69.9 kg .m^{-3}).

The values of the MOE had the same behavior of the values of the basic density, however, there is no statistical difference between the different genetic material and plant spacing variation.

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