EFFECTS OF PLANT SPACING ON THE PHYSICAL, CHEMICAL AND ENERGY PROPERTIES OF *EUCALYPTUS* WOOD AND BARK

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ROCHA MFV, VITAL BR, DE CARNEIRO ACO, CARVALHO AMML, CARDOSO MT & HEIN PRG. 2016. Effects of plant spacing on the physical, chemical and energy properties of *Eucalyptus* wood and bark. Plant spacing affects tree growth and, consequently, the properties of its wood. However, not much is known about how plant spacing influences changes in wood properties. The aim of this study was to evaluate the influence of plant spacing on wood density as well as chemical and energy properties in *Eucalyptus* wood and bark. Clones of *Eucalyptus grandis* × *E. camaldulensis* were grown in five different plant spacings, namely, 1.5, 3.0, 4.5, 6.0 and 9.0 m^2 (representing 3.0 m × 0.5 m, 3.0 m × 1.0 m, 3.0 m × 1.5 m, 3.0 m × 2.0 m and 3.0 m × 3.0 m respectively) in Itamarandiba, northern Minas Gerais, Brazil. The findings indicated that plant spacings significantly influence key properties of wood and bark. Trees planted at 4.5 to 9.0 m^2 spacings had wood density approximately 8% higher than the same clones planted in narrow spacing (1.5 m^2). Lignin content from wood of 6.0 and 9.0 m^2 spacing was approximately 12% higher than wood from 3.0 m^2 spacing. The holocellulose was also affected by plant density. However, extractives and insoluble lignin contents did not vary according to the plant spacing. This study showed that, for *Eucalyptus* clones in this region, plantations with wider spacing could lead to production of raw materials with characteristics more suitable for energy purposes.

Keywords: Planting density, wood quality, wood density, holocellulose, forest management

INTRODUCTION

Managed forests for bioenergy production, also called energy forests, supply biomass which can be used as fuel for direct combustion or charcoal. The use of wood as charcoal precursor has been featured in the steel sector (Moreira 2011), especially in Brazil, where vegetable charcoal is used to reduce iron ore and produce 'green steel'. Planting of forests for energy use helps to reduce illegal extraction of wood from natural forests, thereby reducing the pressure on native forests (Brito 2007). In this way, forest industries need to use raw material with adequate properties in order to improve the final quality of their products, increasing the energy efficiency of forests and reducing costs.

In management of planted forests, plant spacing is an important parameter to be considered as it affects growth rate, wood quality, cutting cycle and the economic aspects of the investment (Magalhães et al. 2007). Most studies of plant spacing in plantation forest have focused on the effects of growth conditions on growth and productivity (Gonçalves et al. 2004). It is possible to induce variations in growth rate of trees by interfering in the growth conditions, e.g. via irrigation, fertilisation and spacing (Stape et al. 2010).

There is not much study done on the influence of silvicultural treatments and forest management strategies on wood quality. Most studies of hardwoods were based on growth rate, knot occurrence, grain angle, stem straightness, juvenile wood and reaction wood. Studies involving *Eucalyptus* mainly focused on effects of forestry management on wood properties. These included the effects of rapid growth on wood properties (Bamber et al. 1982), spacing on biomass production (Vital & Della 1987), and initial spacing and thinning intensity on wood anatomical properties (Malan et al. 1992). Wood density of trees planted with lower plant spacing increases rapidly with increasing distance from the pith, showing no tendency to level off towards the bark (Miranda et al. 2009). On the other hand, trees growing more freely have maximum density of wood fairly early in life, resulting in stems with large proportions of mature wood of relatively uniform density. Wood anatomic features of *E. globulus* were not affected by thinning and spacing (Miranda et al. 2009).

The hypothesis of this study was that plant spacing controlled wood and bark variations of trees from fast-growing plantation. Thus, this study was aimed at evaluating the influence of plant spacing on density, chemical composition and energy properties of wood and bark from 7-year-old *E. grandis* × *E. camaldulensis* (hereafter *Eucalyptus* hybrid) managed for energy purposes.

MATERIALS AND METHODS

Plant materials

A total of 15 commercial 7-year-old *Eucalyptus* hybrids were felled in Itamarandiba, northern of Minas Gerais, Brazil. The plantation experiment belongs to ArcelorMittal Jequitinhonha Company and was established in December 2002 in a randomised design, as described in Rocha (2011). The trees were planted under five plant spacings and replicated in three blocks. The treatments were 3 m × 0.5 m (1.5 m^2), 3 m × 1 m (3.0 m^2), 3 m × 1.5 m (4.5 m^2), 3 m × 2 m (6.0 m^2) and 3 m × 3 m (9.0 m^2). Each block consisted of six planting lines (3 m distance between lines) with 28 trees planted in each line (the distance between the trees varied according to spacing) totalling 168 trees. In each block, the first two and the last two planting lines, and the first two and the last two trees of each line were considered as edges. Thus, 120 trees were classified as edges whereas 48 trees inside the block belonged to the sample unit. Of the 48 trees per treatment, 3 trees for each treatment were selected for the study, totalling 15 trees for the five treatments. Trees were felled and wood discs (thickness 60 mm) were collected at 0, 25, 50, 75 and 100% of the commercial height (diameter 60 mm) of the stem. Defect-free wedges were collected from the discs for wood characterisation.

Wood and bark characterisation

Two opposing wedges were obtained from each disc for determination of basic density of wood according to NBR 11941 (ABNT 2003). Basic density of bark was calculated using the ratio of mass to volume. Volumes were determined by immersing saturated wood and bark samples in water. The remaining wedges and barks were used for chemical analyses. Wood and bark samples were reduced in size before milling. Wood powder was produced using Wiley laboratory mill according to TAPPI 257 om-52 (TAPPI 2001). Wood powder from each tree was combined in order to form a composite powder sample originating from a single tree. The same procedure was adopted for barks collected at different heights.

Macromolecular composition of the wood of each tree was determined using composite sample. Wood powder was classified using a set of sieves. The fraction that passed through the 40-mesh sieve and retained in the 60-mesh sieve was used as composite sample according to ASTM (2007). Mass of the oven-dried wood samples was determined according TAPPI 264 om-88 (TAPPI 1996).

Extractives content was determined in duplicate, as modification of the standard TAPPI 264 om-88 (TAPPI 1996) in which benzene:ethanol was replaced with toluene:alcohol (2:1 v:v) and alcohol was extracted using soxhlet extractor. Insoluble lignin content was determined in duplicate using Klason method (Dence 1992). The extractives-free powder was prepared in several steps with 72% sulphuric acid to obtain insoluble lignin. Soluble lignin was determined using UV-visible spectrophotometry. The sum of soluble and insoluble lignin values was considered as total lignin (in relation to the dry weight of extractives-free powder). Extractives and lignin contents were expressed as percentages of oven-dry weights of unextracted wood. Percentage remaining after extractions of extractives and lignin (hereafter called as holocellulose content) was determined using the formula below:

$$\%\text{Holocellulose} = 100 - (\%\text{extractive} + \%\text{lignins})$$

Superior calorific values of wood and bark were determined using adiabatic calorimetry pump according to NBR 8633 (ABNT 1983). Estimated error of the repeatability of the superior calorific value measurement was 3%, on average.

Data analysis

The experimental design was completely randomised with five treatments, namely, plant spacings at 1.5, 3.0, 4.5, 6.0 and 9.0 m^2 in triplicates (three trees). Statistical analysis was performed using SPSS software version 19 (2010). The data were subjected to analysis of variance (ANOVA). When significant differences occurred between treatments, mean values were compared using Tukey's test ($p < 0.05$).

RESULTS AND DISCUSSION

Effects of spacing on densities of wood and bark

Results showed that plant spacing affected wood and bark basic densities in *Eucalyptus* plantations but with varying magnitudes. Wider spacings produced denser wood and bark (Figure 1). The wood of clones planted with spacings of 4.5 to 9.0 m^2 (average ρ = 0.55 g cm^{-3}) had significantly higher density compared with clones at 1.5 m^2 (ρ = 0.51 g cm^{-3}) spacing. The effect on bark density was less evident, but trees planted at spacing 9.0 m^2 produced bark with greater density than trees at 1.5 m^2. This difference in wood and bark densities as a function of plant spacing could be due to competition between trees for light, water and nutrients.

These results are different from those reported by Vital and Della (1987) who found that plant spacings from 1.5 to 6 m^2 had no effect on wood density of *Eucalyptus*. Plant spacings between 1.75 and 6.88 m^2 had no effects on growth factors and basic wood density in 30-month-old *E. grandis* (Vital et al. 1981). The amount of wood produced by trees at different plant spacings tend to equalise as the forest grows, reducing variation in biomass production between trees with time (Ferreira 1997). Growth stagnation occurs at younger ages with dense plant spacing (lower than 4 or 5 m^2), while plantations with wider spacing (greater than 6 or 9 m^2) tend to exhibit growth stagnation at older ages. This behaviour is important from an economic point of view as companies can save on costs of deployment and harvesting operations and wood transportation when using wider spacing in their plantations. However, when considering the same section for the same harvest period, denser planting provide greater volume of wood compared with wider planting.

When plantation is established for charcoal production, the use of denser wood results in denser charcoal which allows higher production by gravimetric operation in the oven. For example, *Eucalyptus* clones aged 7 years old with wood densities ranging from 0.52 to 0.59 g cm^{-3} had higher wood-to-charcoal yield (Trugilho et al. 2001). Thus, clones planted with wider spacing will produce higher wood density and, therefore, higher yield in charcoal. This assumption may

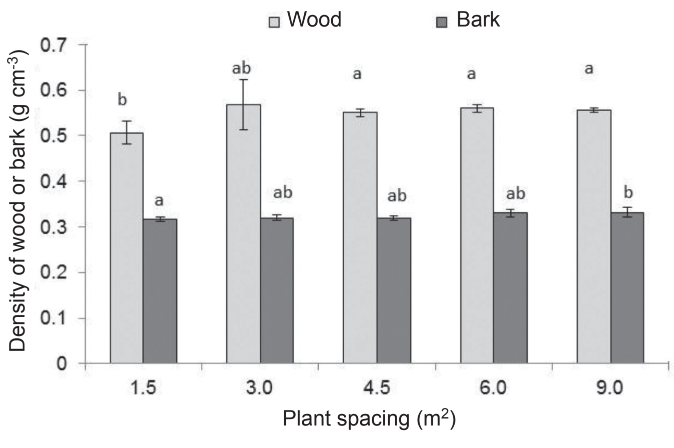

Figure 1 Mean basic densities of wood and bark in *Eucalyptus* trees planted at different spacings; means with the same letter are not significantly different (Tukey test, $p > 0.05$)

be useful for countries like Brazil where many ferrous metallurgy industries use vegetable charcoal as bioreducing agent for converting iron ore into green steel in blast furnaces. However, some studies of conifers reported lower wood density with greater spacing (Kennedy 1995, Hapla 1997).

Effect of spacing on macromolecular composition of wood

Plant spacing affected the chemical composition of *Eucalyptus* wood (Figure 2). Proportions of chemical components in the wood were similar to those reported by Trugilho et al. (2003) and Moulin (2015). In the present study, there was significant effect of plant spacing on insoluble lignin and holocellulose contents. The acid-soluble lignin ranged from 3.46 to 3.77% but there was no clear tendency of increase according to treatments. Extractives as well as total and soluble lignin contents did not vary significantly between plant spacings (results not shown).

Total lignin content of wood was higher in trees planted at wider spacings (Figure 2). Lignin content of wood from 6 and 9 m^2 spacings (~ 29%) was about 12% higher compared with 3 m^2 spacing (~ 26%). This result was consistent with reports by Moulin et al. (2015) who reported that 12-month-old *Eucalyptus* wood cultivated at wider spacing produced higher lignin content. However, unlike lignin, holocellulose showed the opposite trend whereby, wood from trees planted at narrower spacings had higher holocellulose content (Figure 2). The extractives content of wood from trees at 9 m^2 (3%) spacing was 40% higher than wood from trees at 4.5 m^2 spacing (2%). However, due to high variability, there was no significant difference between extractives contents of wood produced in these treatments (Figure 2). For soluble lignin, there was variation of 3.5 to 3.8% between samples, but there was no effect of spacing (results not shown).

The proportions of chemical components in the wood varied according to spacings but no significant trend was observed. Thus, chemical composition of *Eucalyptus* wood appeared to depend on many factors including provenance and irrigation. For example, Downes et al. (2014) examined the properties of 10-year-old *E. globulus* at three sites in Australia but did not find any effects of site on cellulose content. In one of the sites (Scott River), cellulose content of *E. globulus* was 1% higher than in the other two sites, but with no statistical significance (p = 0.057). Chemical composition of *Eucalyptus* wood produced at different spacings shows that relationship between chemical compositions and plant spacings depends on age of the plants and also genetic material (Moulin et al. 2015). The authors investigated wood of two clones of *E. grandis* × *E. urophylla* aged 6 and 12 months and found that higher lignin content was available in trees planted at greater spacings. However, age and irrigation had no effects on lignin content

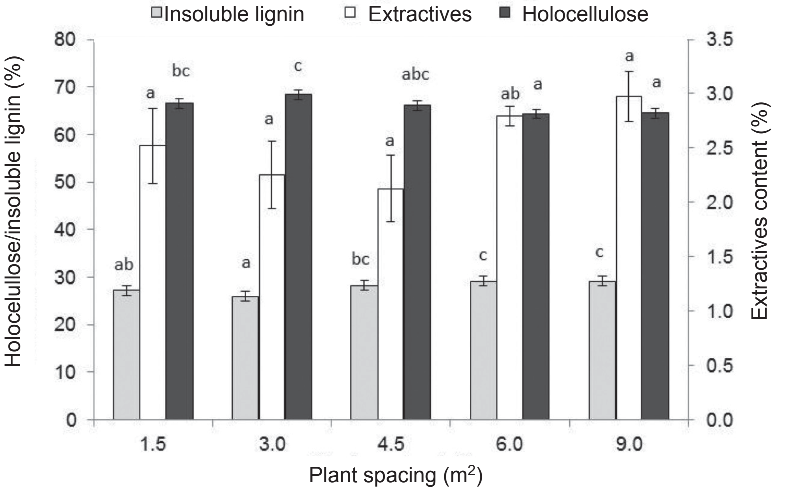

Figure 2 Chemical compositions of wood in *Eucalyptus* trees planted at different spacings; means with the same letter are not significantly different (Tukey test, p > 0.05)

although the former was the main factor affecting chemical composition of wood.

The competition among plants for light is much more intense in smaller spacings due to the need of the trees to expand their leaf surface for carbon assimilation. Thus, the general trend of increasing insoluble lignin in wood as shown in Figure 2 can be explained by greater increase in height of trees cultivated at larger spacing with expected greater percentage of juvenile wood in its trunk compared with trees at smaller spacing. Juvenile wood has higher lignin content compared with mature wood (Zobel & Van Buijtenen 1989). Lignin content in the wood investigated in this study was adequate for charcoal production (Figure 2). Lignin is one of the chemical components that contributed most to gravimetric yield due to its high resistance to thermal degradation (Santos 2010). In addition, it contributes to higher levels of fixed carbon in charcoal due to higher percentage of elemental carbon compared with nitrogen and oxygen. Thus, the larger the spacing of plantations, the higher the lignin content of the wood, and consequently, the higher the gravimetric yield in charcoal.

Characterisation of biomass energy

There were no significant variations in calorific values of wood and bark between treatments (Figure 3). Gross calorific value of the wood ranged from 4337 (4.5 m^2 spacing) to 4425 kcal kg^{-1} (9.0 m^2). For bark, gross calorific value ranged between 3980 and 4093 kcal kg^{-1} for spacings of 3.0 and 6.0 m^2 respectively.

The Pearson's correlation between gross calorific values of wood and bark was 0.35 while that between density of wood and bark, 0.34. This study showed that plant spacing did not affect heating value of wood (Figure 3). However, as spacing affected biomass density (Figure 1) and insoluble lignin content (Figure 2), larger spacings would result in trees presenting higher density and lignin content. Thus, it is reasonable to assume that spacing indirectly affects calorific value of charcoal. This study indicated that larger plant spacing could lead to production of raw materials with characteristics more suitable for energy purposes.

CONCLUSIONS

The findings of this study indicated that plant spacing influenced key properties of wood and bark. Wider plant spacings produced trees with denser woods. The *Eucalyptus* clones planted at 4.5 to 9.0 m^2 spacings presented wood density (0.55 g cm^{-3}) approximately 8% higher than trees planted at 1.5 m^2 spacing (0.51 g cm^{-3}). There were significant effects of plant spacing in insoluble lignin and holocellulose contents while extractives and soluble lignin contents were not affected. Lignin content of the wood produced at 6.0 and 9.0 m^2 (~29%) spacings were about 12% higher than wood produced at 3.0 m^2 spacing (~ 26%). Wider plant spacing of these *Eucalyptus* clones led to production of raw

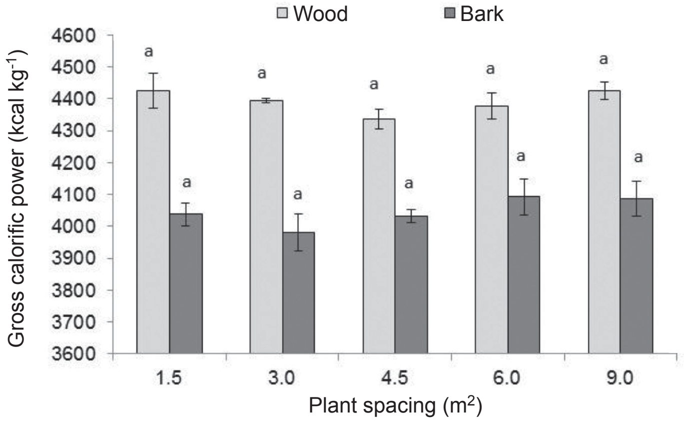

Figure 3 Variation in gross calorific values of wood and bark in *Eucalyptus* planted at different spacings; means with the same letter are not significantly different (Tukey test, $p > 0.05$)

materials with characteristics more suitable for energy purposes.

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