Effect of stocking density on energetic productivity of an eucalyptus stands managed under a short rotation system

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ABSTRACT: This study aimed to evaluate the effect of six stocking densities on growth, yield and energetic potential of an eucalyptus clonal stand established under a short rotation system in Jataí, Goiás State, Brazil. A randomized block design was used with six stocking densities (3 x 0.5 m, 3 x 1 m; 3 x 1.5 m; 3 x 2 m; 3 x 2.5 m and 3 x 3 m), distributed in a various size of plots (15 m², 30 m², 45 m², 60 m², 75 m² and 90 m², respectively) using three replications each. The yield and energetic potential of the stand were evaluated by basal area, volume, wood biomass, fixed carbon, higher calorific value and energy density of wood. From the yield biomass data per hectare it was estimated the area required to meet the demand of a thermal power plant with an installed capacity of 1 MW. For the values of basal area, volume, wood biomass and fixed carbon there was significant difference ($p < 0.05$), with the highest values obtained in the most dense stands. Higher calorific value and energy density of wood has no significant effect by the stand density. The area required to meet the demand of an energy generation unit is directly related with stand density. For the environmental conditions of Jataí, Goiás, Brazil, it is recommended to use the stocking density of 3.0 m x 0.5 m in short rotation, aimed at energy production.

Palavra-chave: Planting densities, bioenergy, energy forest.

Efeito do espaçamento na produtividade energética de um povoamento de eucalipto manejado em regime de curta rotação

RESUMO: Este estudo teve como objetivo avaliar o efeito de seis densidades de plantio no crescimento, produção e potencial energético de um povoamento clonal de eucalipto implantado em Jataí-GO em regime de curta rotação. Foi utilizado o delineamento em blocos casualizados, com seis densidades de plantio (3.0 m x 0.5 m, 3.0 m x 1.0 m; 3.0 m x 1.5 m; 3.0 m x 2.0 m; 3.0 m x 2.5 m and 3.0 m x 3.0 m) distribuídos em parcelas de área variável (15 m², 30 m², 45 m², 60 m², 75 m² e 90 m², respectivamente) e três repetições. A produção e o potencial energético do povoamento foram avaliadas pela área basal, volume, biomassa de madeira, carbono fixado, poder calorífico superior e densidade energética da madeira. A partir dos dados de produção em biomassa por hectare foi estimada a área necessária para atender uma termelétrica com capacidade instalada de 1 MW. Para os valores de área basal, volume, biomassa de madeira e carbono fixo houve diferença significativa ($p < 0,05$), sendo os maiores valores obtidos no espaçamento mais adensado. O poder calorífico superior e a densidade energética da madeira não foram afetados pelos espaçamentos estudados. Verificou-se que a área necessária para atender à demanda de uma unidade de geração energética apresenta relação direta com o aumento do espaçamento. Para as características edafoclimáticas de Jataí-GO, recomenda-se a utilização do espaçamento 3,0 x 0,5 m em curta rotação visando a produção de energia.

Keywords: densidades de plantio, bioenergia, floresta energética.

1. INTRODUCTION

Forest biomass has the potential for power generation, with the advantage of being a source of clean and renewable energy, in addition to job creation (GOŁASZEWSKI et al., 2012). It can also be converted into solid, liquid or gaseous fuels, which will be used to generate electricity, and to provide heat for various industrial processes. This energy recovery can be made by direct combustion or thermochemical, biochemical and mechanical processes.

A good strategy to be used, particularly by countries with fragile economies due to the dependence on fossil fuels, is the adoption of policies able to provide the development of new alternative energy sources, preferably renewable, contributing to a better balance of their respective energy matrices, in the short and medium term and to the diversification and decentralization of the power generation matrix.

The use of biomass for energy production aims to reduce external energy dependence and a greater certainty regarding demand supply, something that many of the fuels normally used do not provide. Moreover, it is one of the energy sources that allow one of the highest rates of job creation by monetary resources invested (BRITO, 2007).

Compared to other renewable energy sources, forest biomass has additional favorable characteristics, since forests have a great diversity of product offering, whose potential and conversion into energy exceed the original prospected use (BRAND et al., 2015).

As a result of technological development and low costs that represent its efficient use (CORTEZ et al., 2008), studies on the potential of energy forests have been intensified in recent years.

Therefore, reforestation with fast-growing species, combined with short-term cutting cycles, taking advantage of the natural ability of regrowth and use of dense spacing, is presented as an alternative to meet the growing demand for biomass. In this context, this study was conducted to evaluate the effect of stocking densities on growth and energetic potential of a clonal stand of eucalyptus established in Jataí, Southwest region of the state of Goiás, Brazil.

2. MATERIAL AND METHODS

The study was conducted in Jataí, Southwest region of the state of Goiás, Brazil, in an area located at 17°56'S and 51°43'O. The climate in the region is classified as mesothermal, with dry and rainy seasons (Cw, according to the Köepen classification). The soil is classified as oxisoil.

The experiment was carried out using seedlings of clone 1277 (hybrid *E. grandis* x *E. camaldulensis*). The experimental design was of randomized blocks, with three replications. The treatments were the six planting densities: 3.0 m x 0.5 m, 3.0 m x 1.0 m; 3.0 m x 1.5 m; 3.0 m x 2.0 m; 3.0 m x 2.5 m and 3.0 m x 3.0 m. and three replications.

For the assessment of yield and those characteristics that express the energetic potential of the stands, a model tree was selected in each plot, that is, the tree with a dbh (diameter at 1.3 m above ground level) with a value related to the quadratic mean diameter of the plot.

From dbh data of each sampled tree, the sectional area was calculated and, therefore, the basal area of each planting densities evaluated.

The total volume of the sampled trees was obtained by stem measurement performed by the Smalian scaling method, by measuring the dbh over bark in different heights 2.0; 4.0; 6.0 m, up to 5 cm of the stem.

For density and calorific value determination in each sampled tree, 2.5 cm thick discs were taken at 0, 25, 50, 75 and 100% of their commercial height, considered up to a minimum diameter over bark of 5 cm. From these discs, samples were taken for the determination of basic density in the laboratory by the immersion method, according to the standard procedures described in ABNT/ NBR 11941/2003.

Subsamples of wood were taken from all discs for determination of higher calorific values, according to procedures described in ABNT/ NBR 8633/1984, using an adiabatic bomb calorimeter.

The energy density of wood was calculated by multiplying the higher calorific value of wood by basic density obtained before. Subsequently, the unit energy density obtained was converted into energy density per hectare.

The estimated dry matter of wood was obtained by multiplying the average basic density by the total volume with bark.

Considering that the carbon contents fluctuate between 40 and 50% of the plant's dry weight (WATZLAWICK et al.,

2003), for the estimates of carbon stored in the stems of trees carbon stored in the shaft of trees, the factor 0.45 was used.

The data obtained at 24 months for basal area, volume, unit energy density of wood, higher calorific value, dry matter of wood and fixed carbon were subjected to analysis of variance and, for significant stand density effects the Scott-Knott test at 5% significance was used.

For the evaluation of the potential use of eucalyptus firewood for energy generation, a simulation of firewood consumption was performed as well as the area required to meet the demand of a thermal power plant with an installed capacity of 1 MW was estimated, following the methodology adopted by Müller et al. (2005b).

Initially, the annual energy production of the thermal power plant was calculated by the expression:

$$EP = (P \times 24\,hours \times 365\,days \times fa \times fl) \qquad \text{(Eq. 1)}$$

where: EP = energy production over a year (KWh); P = energy power of the thermal power plant (KW); fa = availability factor of the thermal power plant; fl = load factor of the thermal power plant.

The values of availability and load factors used were 0.97 and 0.60, respectively, as adopted by Müller et al. (2005b).

According to Goldemberg (2000), the overall efficiency of primary energy conversion into useful energy is approximately one third. The value obtained for EP was multiplied by 3.33 for the estimation of thermal energy consumption (TEC).

Firewood consumption for power generation was obtained by:

$$F = \left(\frac{TEC \times 860\,kcal/kWh}{LHV} \right) \div 1000 \qquad \text{(Eq. 2)}$$

where: F = amount of firewood required for power generation by the thermal power plant; TEC = thermal energy consumption (KWh); LHV = lower calorific value of wood (kcal Kg^{-1}).

Assuming an 80% efficiency in the conversion tree $\Rightarrow$ firewood $\Rightarrow$ heat (MÜLLER et al., 2005b), the total firewood consumption required was obtained by dividing the value of F obtained in the previous expression by 0.8.

The area required to meet the demand for firewood as a function of installed capacity was calculated by dividing firewood consumption by wood production in tons per hectare.

3. RESULTS

Table 1 shows the result of the Scott-Knott test for basal area and total volume, at 24 months and different spacings evaluated.

Wood density and dry mass yield of wood and carbon as a function of planting density are shown in Table 2.

The higher and lower calorific values, as well as energy density for the six evaluated spacings, are shown in Table 3.

Firewood consumption and the area required for the installation of a thermal power plant with production capacities equivalent to 1 MW are shown in Table 4.

It was found that the area required to meet the demand of a unit of energy generation is directly related with stand density and, the less dense, the higher the firewood consumption.

Studies with energy eucalyptus forests evaluating dense spacings and short rotations were also conducted by Müller et al. (2005). They also observed an inverse relationship of the planting area required to meet the termal power plant with stand density.

The obtained results corroborate the premise of the purpose of energy crops to achieve a greater dry matter production per unit area and, therefore, greater energy potential, in a shorter time.

Table 1. *Eucalyptus sp.* production, in basal area and volume, as a function of spacing*.
Tabela 1. Produção em área basal e em volume de *Eucalyptus sp.* em função do espaçamento.

Spacing	Basal Area (m² ha⁻¹)	Total Volume (m³ ha⁻¹)
3.0 m x 0.5 m	54.1848 a	299.1933 a
3.0 m x 1.0 m	29.6165 b	208.5600 b
3.0 m x 1.5 m	22.5499 b	129.5800 c
3.0 m x 2.0 m	15.6384 c	120.8100 c
3.0 m x 2.5 m	12.8777 c	100.5067 c
3.0 m x 3.0 m	12.5872 c	87.8733 c
CV (%)	43.09	13.89

*Where: Means followed by the same letter in the column do not differ by the Scott-Knott test at 5%.

Table 2. Density and yield of dry matter and fixed carbon for *Eucalyptus* sp., as a function of spacing*.
Tabela 2. Densidade e produção em massa seca e em carbono fixado de *Eucalyptus sp.* em função do espaçamento.

Spacing	Wood density (g cm⁻³)	Dry matter of wood (Kg ha⁻¹)	Fixed Carbon (kg ha⁻¹)
3.0 m x 0.5 m	0.44 a	131,873.95 a	59,343.28 a
3.0 m x 1.0 m	0.44 a	93,413.96 b	42,036.28 b
3.0 m x 1.5 m	0.47 a	60,805.86 c	27,362.64 c
3.0 m x 2.0 m	0.44 a	53,597.64 c	24,118.94 c
3.0 m x 2.5 m	0.47 a	47,467.63 c	21,360.43 c
3.0 m x 3.0 m	0.45 a	40,023.44 c	18,010.55 c
CV (%)	4.85	14.96	14.96

*Where: Means followed by the same letter in the column do not differ by the Scott-Knott test at 5%.

Table 3. Calorific value and production in energy density of *Eucalyptus* sp., as a function of spacing*.
Tabela 3. Poder calorífico e produção em densidade energética de *Eucalyptus sp.* em função do espaçamento.

Spacing	Higher calorific value (Kcal Kg⁻¹)	Lower calorific value (Kcal Kg⁻¹)	Energy Density (Gcal m⁻³)	Energy Density (Gcal ha⁻¹)
3.0 m x 0.5 m	4668 a	4353.8 a	2.06 a	574.7 a
3.0 m x 1.0 m	4566 a	4196.1 a	2.03 a	391.2 b
3.0 m x 1.5 m	4669 a	4322.4 a	2.20 a	263.0 c
3.0 m x 2.0 m	4609 a	4183.1 a	2.05 a	223.8 c
3.0 m x 2.5 m	4528 a	4209.7 a	2.14 a	199.8 c
3.0 m x 3.0 m	4549 a	4179.7 a	2.07 a	167.2 c
CV (%)	2.88	2.18	5.01	14.91

*Where: Means followed by the same letter in the column do not differ by the Scott-Knott test at 5%.

Table 4. Firewood consumption (t) and area required (ha) to meet the demand as a function of a power of 1 MW.
Tabela 4. Consumo de lenha (t) e área necessária (ha) para atender a demanda em função da potência de 1 MW.

Spacing	Firewood consumption (t)	Required area (ha)
3.0 m x 0.5 m	4,191.90	31.79
3.0 m x 1.0 m	4,349.45	46.94
3.0 m x 1.5 m	4,222.36	69.17
3.0 m x 2.0 m	4,362.96	81.36
3.0 m x 2.5 m	4,335.39	91.40
3.0 m x 3.0 m	4,366.51	109.42
Energy production over a year (Kwh)	5,098,320	
Energy consumption (Kwh)	16,977,406	

4. DISCUSSION

The basal area had a variation of 76.8%, showing a statistical difference in the evaluated spacings, with lower values for larger spacings, demonstrating that the full occupancy of the site by larger spacings has not happened yet. Similar results were obtained by Berger et al. (2002) and Müller et al. (2005b), who observed an increase in basal area with the reduction in the spacing between plants.

The volume presented a behavior similar to the basal area, confirming, according to Berger et al. (2002), that denser spacings show, in terms of total production per hectare, greater basal area and volume per hectare.

There is generally an increased competition for resources in denser spacings, and growth changes with forest age, reaching a peak relatively early, followed by a substantial decline (TSCHIEDER et al., 2012).

The difference in volumetric production from one spacing to another is only dependent on the time required to obtain the full occupancy of the site, with a tendency of a similar maximal yield per unit area for all stocking density. In wider spacings it is expected to obtain, at the end of their rotation, an overall volumetric production similar to that obtained for smaller spacings, which have early growth stagnation, resulting in shorter rotations and smaller individuals (MOSIEJ et al., 2012).

As stated by Müller et al. (2005b), the studied of stand spacings did not effect on wood density.

Wood dry matter showed a declining production tendency, due to the increase in useful area, that is, planting spacing.

The same tendency was observed for fixed carbon, that is, a larger amount of carbon in denser spacings. In the denser spacing there are more trees resulting in in a higher amount of dry matter and carbon at younger ages.

It is noteworthy that the amount of wood stored in a particular site tends to equalize in different spacings over time and, in the highest planting densities, growth stagnation occurs at younger ages and, in plantations with wider spacings, growth stagnation occurs at older ages (MÜLLER et al., 2005b).

Spacing did not affect the higher and lower calorific values nor unitary energy density. It is possible to observe that the average higher calorific value was 4,598 Kcal.Kg⁻¹, while the average lower calorific value was 4,240.8 Kcal.Kg⁻¹, and the average unit energy density was 2.09 Gcal.m⁻³.

Although several authors have reported that there is an increasing tendency of calorific value with the increase in

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planting density. Studies conducted by Rocha et al. (2012) for the hybrid *E. grandis* x *E. camaldulensis* in five initial planting spacings (3.0 m x 0.5 m; 3.0 m x 1.0 m; 3.0 m x 1.5 m; 3.0 m x 2.0 m and 3.0 m x 3.0 m) and evaluations at 48, 61, 77 and 85 months, showed average results for higher calorific values similar to those obtained in this study.

Carvalho; Nahuz (2001) studied the wood of the hybrid *E. grandis* x *E. urophylla* for use as firewood, and obtained an average LHV of 4,078.87 kcal.kg^{-1}.

The values obtained for both HHV and LHV demonstrate that the wood produced in different spacings has the ability to be used in power generation.

In relation to unit energy density, there is a variation from 2.05 to 2.20 Gcal m^{-3}. Lima et al. (2011) found a unit energy density of 2.22 Gcal m^{-3} for 6-year *E. benthamii*. Protásio et al. (2013) evaluated three *E. urophylla* clones and four *E. grandis* clones for the production of energy and charcoal bioenergy found that unit energy density ranged from 2.162 Gcal m^{-3} to 2.574 Gcal m^{-3}.

When energy density per unit area is analyzed, it is possible to observe spacing effect, and the densest spacing presented a higher LHV than the other spacings.

Eloy et al. (2015) assessed the energy productivity of wood biomass of *E. grandis* at three years, and obtained a variation from 190.748 to 387.658 Gcal ha^{-1} for spacings 2.0 m x 1.0 m, 2.0 x 1.35 m, 3.0 m x 1.0 m and 3.0 m x 1.5 m.

Whereas the calorific value expresses the power generation capacity of a fuel during its combustion and that energy density is related to the amount of energy in a given wood volume (LIMA et al., 2011), it can be inferred that the rotation at 24 months presents viable results for energy production.

5. CONCLUSÕES

Spacing significantly influenced the variables dry matter of wood and fixed carbon, and the highest values obtained were found for the spacing 3 x 0.5 m.

The area required to meet the demand of an energy generation unit of 1 MW has a direct relationship with increasing spacing.

For the field characteristics of Jataí, Goiás, Brazil, it is recommended to use the spacing 3.0 m x 0.5 m in short rotation, aimed at energy production.

6. ACKNOWLEDGEMENTS

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