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Scientific Article

GROWTH AND PRODUCTION OF *Eucalyptus* CLONES IN SILVOPASTORAL SYSTEM

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ABSTRACT

The aim of this study was to analyze the growth and production of two eucalypt clones grown in a silvopastoral system in the municipality of Coronel Pacheco, MG, Brazil and select the best volumetric model for the clones in this arrangement. This silvopastoral system is composed of two commercial eucalypt hybrids, GG100 and I144 (*Eucalyptus urophylla* x *Eucalyptus grandis*), at 79 months of age, planted at a spacing of 14.0 x 2.8 meters, *Urochloa decumbens* as forage component and grazing by Brangus cattle. A completely randomized design with two treatments (clones) and six replicates (plots) was used. The diameter with bark of all trees in the plots and the total height of the first ten trees were measured, along with a rigorous volume determination of five trees per diameter class to obtain volumetric production and fit the growth and production model. Forest inventory measurements were taken on six occasions from 21 to 79 months of age. The Spurr (1952) model showed a high quality of fit and adjusted coefficient of determination and low residual standard error. The I144 clone showed a larger diameter and higher productivity compared to GG100 clone. And also, higher wood volume and average annual increment (AAI). Both clones showed a high potential to adapt to the region environment, however, I144 clone was the most suitable for use in silvopastoral systems under similar conditions to the study.

Keywords: Forest modeling; Productivity capacity; Crop-livestock-forest integration

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CRESCIMENTO E PRODUÇÃO DE CLONES DE *Eucalyptus* EM SISTEMA SILVIPASTORIL

RESUMO O objetivo deste estudo foi analisar o crescimento e a produção de dois clones de eucalipto cultivados em um sistema silvipastoril no município de Coronel Pacheco, MG e selecionar o melhor modelo volumétrico para os clones neste arranjo. Este sistema é composto por dois híbridos comerciais de eucalipto, GG100 e I144 (*Eucalyptus urophylla* x *Eucalyptus grandis*), aos 79 meses de idade, plantados em espaçamento de 14,0 x 2,8 m, *Urochloa decumbens* como componente forrageiro e pastoreio de gado Brangus. Foi utilizado delineamento inteiramente casualizado com dois tratamentos (clones) e seis repetições (parcelas). Foram medidos o diâmetro com casca de todas as árvores das parcelas e a altura total das dez primeiras árvores, além de uma cubagem rigorosa do volume de cinco árvores por classe de diâmetro para obter produção volumétrica e ajuste dos modelos de crescimento e produção. O inventário florestal contínuo foi realizado em seis ocasiões, dos 21 aos 79 meses de idade. O modelo de Spurr (1952) apresentou alta qualidade de ajuste e coeficiente de determinação ajustado e baixo erro padrão residual. O clone I144 apresentou maior diâmetro e maior produtividade em relação ao GG100, e ainda, maior volume de madeira e incremento médio anual (IAA). Ambos os clones apresentaram alto potencial de adaptação ao ambiente da região, porém, o clone I144 foi o mais adequado para utilização em sistemas silvipastoris em condições similares às do estudo..

Palavras-Chave: Modelagem florestal; Capacidade produtiva; Integração Lavoura-pecuária-floresta

1. INTRODUCTION

Integrated Crop-Livestock-Forest Systems (ICLFS) are recognized worldwide, and especially in Brazil, as a sustainable alternative for agricultural production (Reis et al., 2021). These systems synergistically integrate different agricultural components, improving land use efficiency, restoring degraded areas, and enhancing environmental resilience (Figueiredo et al., 2017; Jose & Dollinger, 2019). ICLFS have gained prominence in public policies and strategic agricultural planning due to their potential to simultaneously increase productivity and deliver environmental benefits.

The Brazilian government has included the Integrated Crop-Livestock-Forest Systems (ICLFS) in the second phase of the Plan for Adaptation and Low Carbon Emission in Agriculture (ABC+) for the 2020-2030 period to facilitate financing the adoption of these systems in order to promote more adoption of these systems (MAPA, 2021). Over 10 million hectares (Mha) are expected to be planted with ICLFS in this new phase, representing a mitigation potential of over 38 million Mg of CO2 equivalent.

Silvopastoral systems (SPS) represent one of the ICLFS models and are characterized by simultaneous integration of tree and livestock components. They stand out as important alternatives for more sustainable land use, helping to protect against erosion phenomena and contributing to soil water conservation, groundwater recharge and improvement of physical and chemical soil properties (Sartor et al. 2020). These systems also serve as an option to minimize the risks of investments in forestry and livestock farming, as the wood produced at the end of the growth cycle offers potential for diversification and higher income for the landowner (Müller et al., 2011).

Success in establishing a silvopastoral system depends on carefully selecting superior genotypes (clones) to ensure good productivity and the production of high value-added products, which then contributes to greater profitability of the enterprise (Castro et al., 2016; Oliveira et al., 2021). However, in many cases there is still little or no information on the behavior of these clones, especially in certain regions or regarding their use in silvopastoral systems (Oliveira Neto et al., 2010; Stape et al., 2022). Genotypic evaluation includes an analysis of the tree component's dendrometric variables using statistical regression models and/or artificial neural networks (Burkhart & Tomé, 2012; Campos & Leite, 2017; Josephs et al. 2017).

Clones of the *Eucalyptus* genus are generally recommended for integrating these systems due to their characteristics, such as adaptation to the local climate and soil, rapid growth, resprouting capacity, and canopy density (Lima et al., 2018). These clones are primarily intended for pulp and paper production and energy purposes and are grown and evaluated in conventional monocultures (Oliveira et al., 2021). However, many studies have shown that clones and characteristics behave differently when grown under different edaphoclimatic conditions, spacing and cultural practices which can occur in silvopastoral systems, especially in small and medium-sized rural areas, affecting wood productivity and quality (Pavan et al., 2021).

Thus, the objectives of this study were to evaluate the diametric distribution, growth and production of eucalypt GG100 and I144 clones grown in a silvopastoral system in the municipality of Coronel Pacheco, MG, Brazil, and to select the best volumetric model for *Eucalyptus* clones in this arrangement.

2. MATERIAL AND METHODS

2.1 Characterization of the study area

The study was conducted at the Fazenda Triqueda, in Coronel Pacheco, state of Minas Gerais, Brazil (21°37'30"S; 43°17'21.81"W), at an altitude of 652 meters. The topography is dominated by steep areas and the soil is classified as Ferralsols according to the WRB classification (Fao et al., 1998), characterized by low natural fertility and low presence of primary minerals (Santos et al., 2018).

The region's climate is Cwa type (mesothermal) according to the Köppen climate classification, categorized as humid subtropical and characterized by dry winters and rainy summers (Martins et al., 2018). The characteristic vegetation is Semideciduous Seasonal Forest, within the domain of the Atlantic Forest (Rizzini, 1997). Average annual precipitation in the region is about 1,418 mm and is concentrated from October to April, with average temperatures of 18°C from April to September and 22°C from October to March (Müller et al., 2023).

2.2 Characterization of the silvopastoral system

The study was conducted on an 8.5 hectare (ha) area of a silvopastoral system in hilly terrain with an average slope of 23%. The trees were planted in single rows with a spacing of 14.0 x 2.8 meters (255 plants per hectare), with the rows following contour lines of the terrain as described in Resende et al. (2020).

The tree component was planted in November 2009 (6.6 years old at the end of the experiment) with two commercial eucalypt hybrids, GG100 and I144 clones, resulting from genetic crosses between the species *Eucalyptus urophylla* S. T. Blake and *Eucalyptus grandis* W. Hill ex Maiden. The pasture of *Urochloa decumbens* cv. Basilisk had been grown for 15 years without fertilization or acid correction of the soil. Livestock management consisted of intermittent grazing by Brangus cattle at an average stocking rate of 1.5 animal units per hectare. The cattle were introduced 12 months after implementing the silvopastoral system.

Planting fertilization consisted of applying 700 g of dolomitic lime and 350 g of reactive phosphate in the planting pits, and 150 g of formulated NPK 6-30-12 + 1% B fertilizer in side holes. In addition, 200 g of NPK 20-00-20 + 1% B was applied as top dressing per pit. Then, 300 g of NPK 00-00-51 + 1% B was applied per pit at six months after planting, and 300 g NPK 20-00-20 + 1% B was applied per pit at 12 months after planting.

2.3 Experimental design and data collection

A completely randomized design with two treatments (GG100 and I144 clones) and six repetition (plots) was used. Forest inventory measurements were taken on six occasions from 21 to 79 months of age. The

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first five measurements (21, 33, 45, 57, and 69 months) were based on six plots with 10 trees in each treatment in a planting row covering an area of 392 m². At the last measurement after 79 months, the plot consisted of two planting rows with 20 trees and an area of 784 m². The survival rate was calculated using the data from the last measurement.

Diameter at breast height (DBH 1.3 m above ground level) was measured for all trees in the plots using a tape measure, and total height (Ht) for the first 10 trees in each plot was measured with a Forest Vertex IV hypsometer (Haglöf Sweden AB, Långsele, Västernorrland, Sweden). DBH measurements were used to characterize the diameter distribution of the clones, considering diameter classes with a range of 2 cm.

Rigorous scaling was performed for five trees per diameter class based on the number of diameter classes observed at 87 months of age. For this purpose, a non-destructive method was applied on 25 trees of GG100 clone and 30 trees of I144 clone. Direct measurements of the diameters outside the bark were taken at the absolute heights of 0.0, 0.3, 0.7, 1.0, and 1.3 m (DBH). The diameters along the stem above 1.3 m were measured indirectly with a Wheeler Pentaprism at 1.0 m intervals up to a minimum diameter limit of 7.0.

2.4 Diametric distribution

Forest inventory plot data were used to calculate the average diameter of GG100 and I144 clones during the study period. The diameter percentile method was used to calculate and compare the diameter distribution of the stands at 79 months of age. The use of diameter percentiles is widespread in even-aged forests as they are highly correlated with stand characteristics such as age, site index, and maximum diameter (Cunha Neto et al. 1994; Miguel et al. 2014; Mendonça et al. 2015).

The P25, P50, and P75 percentile diameters were used to obtain the distribution of diameters into four equal parts, also known as quartiles, to represent and compare the percentage of lower, middle, and upper diameters. In addition, the percentile of diameter P63 was calculated.

The P63 percentile is closely related to the scale parameter (β) of the Weibull distribution, which represents the inflection point of the curve; its values lie between zero and the limit of I = (1-1/e) = 0.63 (Weibull, 1951; Campos & Leite, 2017).

2.5 Productive capacity

DBH data collected in forest inventory plots from 21 to 79 months were used to calculate productive capacity and the dominant diameter of the plots was calculated. The dominant diameter (dbh_d) is defined as the arithmetic mean of the five largest diameters of the trees in each plot.

The productive capacity was determined by fitting the logistic sigmoidal model (Equation 1) with an index age of 60 months. Site index curves were constructed for the stands of GG100 and I144 clones.

$$y = \beta_0 . \left(1 + e^{(\beta 1 - \beta 2.I)}\right)^{-1} + \varepsilon \qquad \text{(Eq. 1)}$$

In which: y = variable studied; β_i = parameters; e = exponential; I = age in months; and ε = random error, ε ~ NID (0, σ^2).

Mean values of dominant diameters of clones were compared using the Student's t-test at 5% significance level, with the assistance of STATISTICA 13.0 software.

2.6 Volumetric production

The stem volume was obtained by rigorous volume determination using the Smalian formula (Husch et al., 2003) (Equation 2).

$$V = \frac{AS_1 + AS_2}{2} \, x \, L \qquad \text{(Eq. 2)}$$

In which: V = volume of the stem section with bark (m³); AS_1 = cross-sectional area at the beginning of the section (m²); AS_2 = cross-sectional area at the end of the section (m²); L = length of the section (m).

The model proposed by Campos, et al. (1984), was used to estimate total height of all trees (Equation 3).

$$LnHt = \beta_0 + (\beta_1 . dbh^{-1}) + \beta_2 . LnHd + \varepsilon \qquad \text{(Eq. 3)}$$

In which: Ht = total height (m); Ln = neperian logarithm; β_i = parameters; dbh = diameter at breast height, or at 1.30 m aboveground (cm); Hd = dominant height, m; ε = random error, ε ~ NID (0, σ^2).

The volume equations were fitted using the models proposed by Schumacher & Hall (1933) (Equation 4) and Spurr (1952) (Equation 5).

$$LnV = \beta_0 + \beta_1 Lndbh + \beta_2 LnHt + \varepsilon \quad \text{(Eq. 4)}$$

$$V = \beta_0 . (dbh.Ht)^{\beta_1} + \varepsilon \quad \text{(Eq. 5)}$$

In which: V = volume (m^3); Ln = neperian logarithm; β_i = parameters; dbh = diameter at breast height, or at 1.30 m aboveground (cm); Ht = total height (m); and ε = random error, ε ~ NID (0, σ^2).

The best equation was selected based on the coefficient of determination (R^2) (Equation 6), the adjusted coefficient of determination $\overline{R}^2$(Equation 7), the standard error of the estimates (Syx) (Equation 8), and the graphical analysis of the residues (Draper & Smith, 1998).

$$R^2 = 1 - \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 \Big/ \sum_{i=1}^{n} (Y_i - \bar{Y}_i)^2 \quad \text{(Eq. 6)}$$

$$\overline{R}^2 = 100[1 - \frac{(n-1)}{(n-p-1)}(1 - R^2)] \quad \text{(Eq. 7)}$$

$$S_{yx} = \sqrt{\sum_{i=1}^{n} {(Y-\hat{Y})^2}/{(n-k)}} \quad \text{(Eq. 8)}$$

In which: R^2 = coefficient of determination; $\overline{R}^2$ = adjusted coefficient of determination; Syx = standard error of the estimates; Y = observed values; ($\hat{Y}_i$) = estimated values; $\bar{Y}_i$ = arithmetic means of observed values; n = number of observations; p = number of independent variables; and k = number of models parameters.

The identity test described by Graybill (1976) was applied in order to evaluate the feasibility of a single equation for height and volume estimations. The null hypothesis (H_0) was that there was no significant difference between a general equation and specific equations.

3. RESULTS

3.1 Survival and diametric distribution

The percentile diameters for the stands of clones in the current study are shown in Table 1. The P50 percentile for GG100 clone indicates that 50% of the trees in this clone have a diameter of 19.2 cm or less. However, this does not mean that 50% of the volume of the stand is contained within this diameter.

The curvature of the curve changes and the growth rate reaches its maximum at the inflection point. The growth rate decreases from this point onwards until it stabilizes. The GG100 and I144 clones reach their maximum growth period at diameters of 20.8 cm and 21.8 cm respectively (Table 1).

Table 1. Percentile diameters of GG100 and I144 clones at 79 months of age in a silvopastoral system in Coronel Pacheco, MG, Brazil

Tabela 1. Diâmetros percentis dos clones GG100 e I144 aos 79 meses de idade em sistema silvipastoril em Coronel Pacheco, MG, Brasil

Clone	Percentile diameter (cm)			
	P_{25}	P_{50}	P_{63}	P_{75}
GG100	14.9	19.2	20.8	22.0
I144	15.7	20.1	21.8	23.4

For the P75 percentile, 75% of the trees in the I144 clone have a diameter of 23.4 cm or less, while the threshold diameter for the GG100 clone is 22.0 cm. This corresponds to a 6.2% superiority of the diameter of the I144 clone for this specific percentile.

3.2 Productive Capacity

The estimated parameters for the Logistic model and the statistical accuracy tests for GG100 and I144 clones are shown in Table 2. The standard error (Syx) of the residuals for the clones was between 0.96

and 1.22 m, and the coefficient of determination ($\bar{R}^2$) was between 0.96 and 0.98. It was observed that the I144 clone had a better fit than the GG100 clone.

The growth curves of the studied clones were established based on the dominant diameter (dbh_d) among the observed dbh values (Figure 1). It can be observed that the curves generated by the model accurately describe the growth trends of the eucalypt clones in the silvopastoral system, as they have estimated values close to the mean of the observed values. By using the variable dbh_d, the growth curve did not prematurely reach the asymptotic value which indicates stagnation in the stand growth.

Table 2. Parameter estimation and statistics of the Logistic sigmoidal model for eucalypt clones in a silvopastoral system in Coronel Pacheco, MG, Brazil
Tabela 2. Parâmetros estimados e estatísticas para o modelo sigmoidal Logística por clone de eucalipto em sistema silvipastoril em Coronel Pacheco, MG, Brasil

Clone	β_0	β_1	β_2	$S_{y.x}$	$\bar{R}^2$
GG100	25.3259	4.0385	0.0552	1.2216	0.9665
I144	26.1710	5.1605	0.0662	0.9615	0.9830

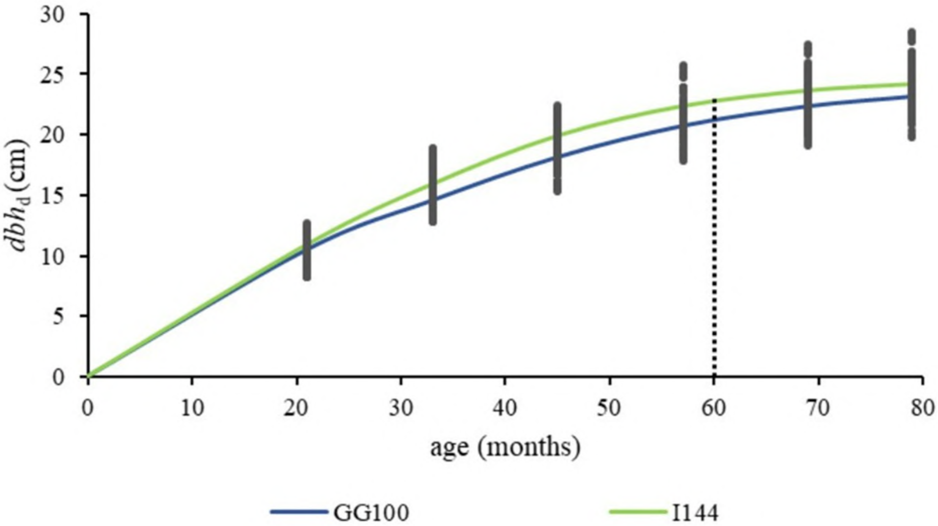

Figure 1. Observed data and growth curves of dominant diameter dbh_d for eucalypt GG100 and I144 clones in a silvopastoral system in Coronel Pacheco, MG, Brazil
Figura 1. Dados observados e curvas de crescimento em diâmetro dominante dbh_d para os clones de eucalipto GG100 e I144 em sistema silvipastoril em Coronel Pacheco, MG, Brasil

The I144 clone had larger dominant diameters than GG100. Clones growth appeared to be similar at an early age, but I144 stood out at an older age. The largest difference between the curves, about 10%, is observed at 45 months of age. The average dominant diameters of the GG100 and I144 clones, at the reference age of 60 months, were 21.2 cm and 22.8 cm, respectively.

3.3 Volume yield

Graybill's (1976) F-test (FH0), which assessed the need for specific model adjustments by clone, was significant for the volumetric model adjustments (326.4400) and not significant for the hypsometric model adjustments (1.0055).

Table 3 shows the parameters and statistical tests for the single hypsometric equation for the two clones generated from the model of Campos et al. (1984).

The residual standard error ($S_{(y.x)}$) indicates that the data dispersion around the adjusted regression was 0.9331 meters, which can be considered small. The adjusted coefficient of determination ($\bar{R}^2$) was 69.15% and explains the variation in height in relation to the variation in dbh.

The residual plot of the hypsometric equation for the GG100 and I144 clones showed a good fit of the model to the observed data, as the data distribution pattern showed uniform variation along the horizontal axis and there were no significant and undesirable trends (overestimation or underestimation) (Figure 2).

The Graybill F-test (FH0) was significant for the volumetric model fits, indicating the need for individual equation fitting for GG100 and I144 clones. Table 4 shows the parameters and statistics for the Schumacher & Hall (1933) and Spurr (1952) models. According to Campos & Leite

Table 3. Parameter estimates and statistics for the Campos et al. (1984) model for eucalypt clones in a silvopastoral system at Coronel Pacheco, MG, Brazil
Tabela 3. Estimativas dos parâmetros e estatísticas para o modelo de Campos et al. (1984) para clones de eucalipto em sistema silvipastoril em Coronel Pacheco, MG, Brasil

Clone	Parameters	Estimates	Standard error	P-value	$S_{y.x}$	$\bar{R}^2$
GG100 and I144	β_0	1.5875	0.2050	<0.05	0.9331	69.15
	β_1	-7.2627	0.8988	<0.05		
	β_2	0.6191	0.0560	<0.05		

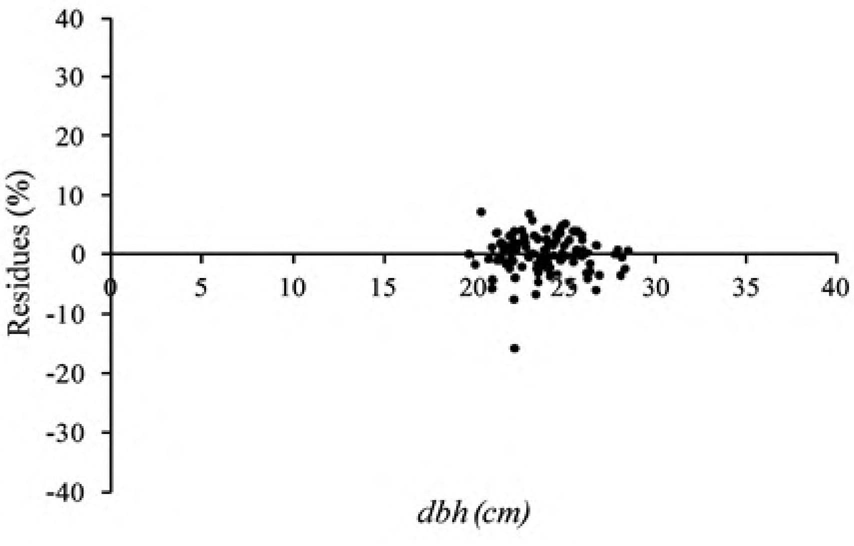

Figure 2. Residual plot for the hypsometric equation of eucalypt GG100 and I144 clones in a silvopastoral system in Coronel Pacheco, MG, Brazil
Figura 2. Gráfico de resíduo para a equação hipsométrica para os clones GG100 e I144 de eucalipto em sistema silvipastoril em Coronel Pacheco, MG, Brasil

(2017), these models are commonly used in studies on *Eucalyptus* spp., with the Schumacher & Hall (1933) model generally providing better fits with unbiased estimates and the Spurr (1952) model being more flexible in data fitting.

Both models showed a similar quality of fit, with high adjusted coefficients of

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determination and low residual standard errors. However, negative signs in the Schumacher & Hall (1933) model were observed in estimating the β_2 parameter for both clones, indicating inconsistency in the estimation of these coefficients, as height showed a positive correlation with tree volume. The p-value for the parameter was similarly not significant, indicating random variation in the relationship between the variables (dbh and Ht) in estimation of the values from the model. Therefore, the model proposed by Spurr (1952) was adopted for estimating clone wood volume.

The residuals of the volumetric equation fitted with the Spurr (1952) model for GG100 and I144 clones are shown in Figure 3.

The wood and average annual increment (AAI) values (Table 5), which were determined at 79 months of age, showed no statistically significant differences between the clones. However, I144 clone had a 6.34%

Table 4. Parameter estimates and statistics for the Schumacher & Hall (1933) and Spurr (1952) models for eucalypt clones in a silvopastoral system at Coronel Pacheco, MG, Brazil
Tabela 4. Estimativas dos parâmetros e estatísticas para os modelos de Schumacher & Hall (1933) e Spurr (1952) para os clones GG100 e I144 em sistema silvipastoril em Coronel Pacheco, MG, Brasil

Modelo	Clone	Parameters	Estimates	Standard error	P-value	$S_{y.x}$	$\bar{R}^2$
Schumacher & Hall (1933)	GG100	β_0	-5.5535	1.2963	<0.05	0.0565	77.32
		β_1	2.1473	0.2449	<0.05		
		β_2	-0.5319	0.4369	0.238		
	I144	β_0	-6.9766	0.6003	<0.05	0.0552	92.80
		β_1	2.2213	0.1824	<0.05		
		β_2	-0.1922	0.2204	0.393		
Spurr (1952)	GG100	β_0	-8.2945	1.0366	<0.05	0.0624	72.42
		β_1	0.7927	0.1054	<0.05		
	I144	β_0	-9.0745	0.9504	<0.05	0.0803	81.12
		β_1	0.8628	0.0941	<0.05		

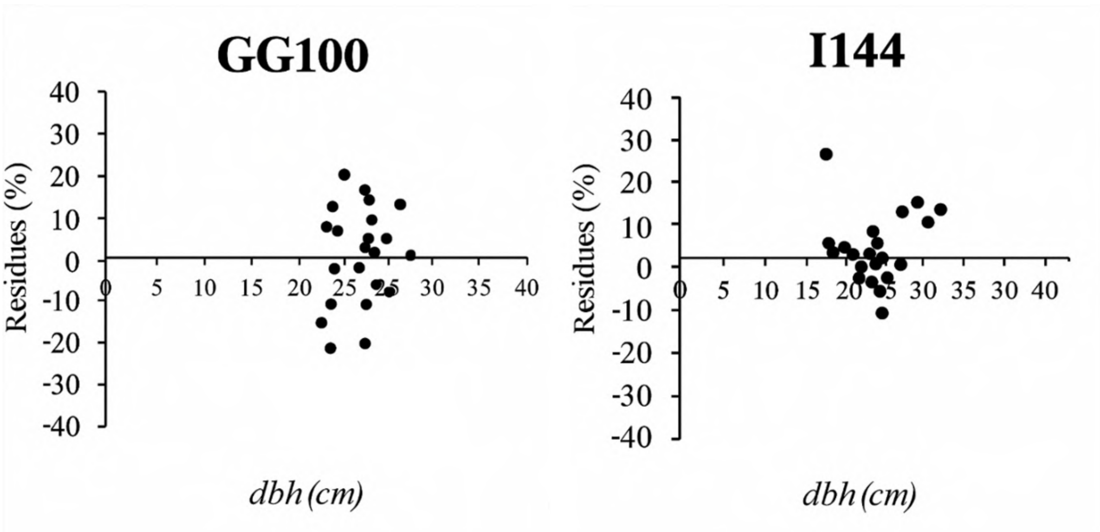

Figure 3. Residual plots of volumetric equations for eucalypt clones in a silvopastoral system in Coronel Pacheco, MG, Brazil
Figura 3. Gráficos de resíduo das equações volumétricas para os clones de eucalipto em sistema silvipastoril em Coronel Pacheco, MG, Brasil

higher wood volume and a 6.34% higher AAI value than GG100 clone, which in practice represents a superiority that should be taken into account when selecting genetic material.

4. DISCUSSION

4.1 Survival and diametric distribution

The analysis of the diametric structure enables evaluating the behavior of the genetic material in relation to factors that influence tree growth (Eufrade-Júnior et al. 2021). The canopy structure of eucalypts clones in silvopastoral systems can negatively influence the productive characteristics of the forage, given its interception of solar radiation and competition for growth resources in the initial crop establishment stages (Bosi et al., 2020; Stape et al., 2022). Although the clones under study are plastic with a high capacity to adapt to various growing conditions, I144 clone is efficient in the use of potassium, which allows it to establish itself in soils with lower potassium availability, while GG100 clone is efficient in translocating calcium to the aerial part (Pinto et al., 2011; Maciel et al., 2022). These characteristics facilitate indicating species according to the environmental conditions in which they will be inserted, favoring higher survival and growth rates.

Table 5. Volume and productivity (AAI) of eucalypt clones in a silvopastoral system, at 79 months of age, in Coronel Pacheco, MG, Brazil
Tabela 5. Volume e produtividade (IMA) dos clones de eucalipto em sistema silvipastoril, aos 79 meses de idade, em Coronel Pacheco, MG, Brasil

Clone	Volume (m^3 ha^{-1})	AAI (m^3 ha^{-1} $year^{-1}$)
GG100	134.3 ^{a}	20.4 ^{a}
I144	142.8 ^{a}	21.6 ^{a}

It is recommended to use percentile diameters in managing unthinned eucalypt stands and in selecting trees for selective thinning due to the simplicity of model fitting (Oliveira Neto et al., 2010; Binoti et al. 2012). According to Farias et al. (2021), percentile diameter models in combination with the clutter model tables allow a segmented volume measurement of the stand up to each of the predicted percentile diameters and also in between.

The I144 clone showed a larger diameter than GG100 in all percentiles analyzed, with the difference in diameter tending to increase with increasing percentile value. As the clones are in the same area and under the same management, the variation in diameter growth between the clones is attributed to genetic variation between the individual hybrids (Lin et al., 2013).

Therefore, I144 clone proved to be the most productive genetic material in terms of stem diameter compared to GG100 for the studied silvopastoral system, indicating a higher potential for wood production.

4.2 Productive capacity

The productive capacity of a site indicates its potential for timber production based on its specific environmental conditions and the silvicultural techniques applied. The interaction between these factors and the genetic material indicates the productive capacity of the clone for the site, which is determined by examining an indicator such as diameter, dominant height, volume, etc. (Campos & Leite, 2017; Ataíde et al., 2021).

A good fit was achieved for both modeled genetic materials. The residual standard error ($S_{(y.x)}$), which accounts for the data dispersion around the fitted equation, was found to be low for both clones. The adjusted coefficient of determination showed high values for both clones, indicating that 96.65% and 98.30% of the variation in dominant diameter dbh_d for GG100 and I144

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clones, respectively, can be explained by age variation.

Diameter is generally not used as an indicator of productive classification in dense populations, as it is strongly influenced by competition between individuals. However, DBH (diameter at breast height) can be used as an indicator of productive capacity classification in populations with low regular mortality, as in the silvopastoral system studied, without inconsistency due to this variable (Avery & Burkhart, 1994).

Leite et al. (2011) found that the use of the dominant diameter variable (dbh_d) for production capacity classification compared to estimates of dominant height (Hd) in *Eucalyptus urophylla* x *Eucalyptus grandis* clone stands in the Santa Bárbara/MG region fitted the data well, suggesting the possibility of its use for the purpose of classifying productive capacity.

As the nutritional and soil conditions were similar for both clones, the superiority of I144 is due to the intrinsic characteristics of the species itself, characterized by being more tolerant to drought and more productive in low water availability conditions when compared to GG100 clone (Pita-Barbosa et al., 2016; Müller et al., 2017). Winter in the study area is characterized by low temperatures and rainfall rates, with averages close to 38 mm per month, which favors development of the clone and its productive capacity (Brasiliense et al., 2020).

In this context, the silvopastoral system emerges as a viable option to reduce competition between species and the demand for growth resources. This occurs because the shade provided by trees reduces ambient and soil temperatures, increases air humidity, and reduces the evapotranspiration rate, leading to increased soil moisture and consequently productivity (Cárdenas & Ibrahim, 2019; Bieluczk et al., 2020). Furthermore, higher soil water levels and milder temperatures can lead to a higher nitrogen mineralization rate in the soil, faster litter decomposition, and an increase in nitrogen cycling and of other nutrients, bringing advantages to C3 plants (de Abreu et al., 2020).

4.3 Volumetric yield

The choice of the Spurr (1952) model to estimate the volume of GG100 and I144 clones instead of the Schumacher & Hall (1933) model due to inconsistencies in estimating the β_2 parameter of this model was also confirmed by Schettini et al. (2021) and de Aguiar Júnior et al. (2023).

The superiority of I144 clone over GG100 is confirmed by other studies. Matias (2016) evaluated GG100 and I144 clones in three different silvopastoral systems: (3 x 2) + 20 m (435 plants ha^{-1}), and (2 x 2) + 9 m (909 plants ha^{-1}), and of 9 x 2 m (555 plants ha^{-1}), in the municipality of Prudente de Morais, MG, Brazil. Schettini et al. (2021) also observed better performance of I144 clone compared to GG100 (AAI of 25.70 m^3 ha^{-1} year and 23.31 m^3 ha^{-1} year, respectively) grown at a spacing of 6x4 m (416 plants ha^{-1}) after 96 months.

In comparing different eucalypts clones to evaluate forage mass in Prudente de Morais, MG, established in crop-livestock-forest integration with double rows (3 x 2) + 20 m, Guimarães et al. (2018) also found that there were no significant differences in the production of signal grass, but observed that it presented a better chemical composition when cultivated under I144 clone, with high crude protein and phosphorus levels and low neutral detergent fiber content when compared to GG100 and VM 58 (*E. grandis* x *E. camaldulensis*) clones. The I144 clone presents physiological growth adaptations, directing photoassimilates to root growth to the detriment of the aerial part, which facilitates its adaptation to areas subject to water restrictions and lower nutrient availability (Maseda & Fernández, 2016).

5. CONCLUSION

- Different *Eucalyptus* clones established in silvopastoral systems have different dendrometric characteristics and growth rates, which directly affect allometric relationships;
- Both clones showed high potential to adapt to the environment in the studied region with high survival rates;
- The I144 clone showed greater production potential compared to clone GG100 clone due to its larger diameter and greater productive capacity;
- As the nutritional and soil conditions were similar for both clones, the superiority

of I144 clone is due to the intrinsic characteristics of the species itself, such as its adaptation to areas subject to water restrictions and lower nutrient availability;

• Data from I144 clone fitted better to the Logistic model and this clone showed higher productive potential than GG100 clone;

• The growth and production differences made it necessary to adapt the volumetric equations individually for each clone, with the Spurr (1952) model providing the best fits.

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AUTHOR CONTRIBUTIONS

Pena RF: Conceptualization, Metodology, Analysis of results, Writing - original draft, Writing - review and editing; Müller MD: Conceptualization, Analysis of results, Writing - original draft, Writing - review and editing, Supervision and coordination of research; Oliveira Neto SN: Conceptualization, Analysis of results, Writing - original draft. Writing - review and editing, Supervision and coordination of research; Paciullo DSC: Conceptualization; Gomes GSL: Writing - review and editing; Aguiar Júnior AL: Metodology, Analysis of results.

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