HYPSOMETRY AND VOLUMETRY OF *Eucalyptus urograndis* IN A CROP-FOREST INTEGRATION SYSTEM

Stephany Diolino Cunha[1]*, Vagner Santiago do Vale[2], Tatiana Vieira Ramos[3], Matheus da Silva Araújo[4]

[1*]Universidade Federal de Lavras, Programa de Pós-Graduação em Engenharia Florestal, Lavras, Minas Gerais, Brasil - *cunhaflorestal@outlook.com
[2]Universidade Estadual de Goiás, Departamento de Engenharia Florestal, Ipameri, Goiás, Brasil - vsvale@hotmail.com
[3]Universidade Estadual de Goiás, Docente, Ipameri, Goiás, Brasil – tatiana.ramos@ueg.br
[4]Universidade de São Paulo, ESALQ/USP. Programa de Pós-Graduação em Solos e Nutrição de Plantas, Piracicaba, São Paulo, Brasil - araujomatheus@usp.br

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Resumo

Hipsometria e volumetria do Eucalyptus urograndis em sistema integração lavoura-floresta. Devido ao impacto positivo que a espécie apresenta para economia do Brasil, o eucalipto é atualmente a essência florestal mais utilizada. O objetivo deste trabalho foi avaliar diferentes modelos hipsométricos e volumétricos para clones de *Eucalyptus urograndis (Eucalyptus urophylla S. T. Blak e Eucalyptus grandis W. Hill ex Maiden)* em sistema Integração Lavoura-Floresta (ILF). As árvores foram avaliadas aos 7 anos de idade e arranjadas em fileiras duplas, ocupando 20,76% da área total do sistema. Os indivíduos foram submetidos a uma cubagem rigorosa, segundo o método desenvolvido por Smalian, a intervalos de um metro, até altura total. Para os dados de altura coletados foram avaliados os modelos: Linear, Trorey, Stofels, Curtis, Henriksen, Prodan, Chapman & Richards, Petterson e Bailey & Clutter. Para os dados de volume, foram utilizados os modelos de Spurr, Hohenald-Krenn, Stoate, Schumacher Hall, Meyer, Husch, Ogaya e Takata. Os resultados foram determinados através do coeficiente de determinação (R^2), erro padrão da estimativa em porcentagem (Syx%), significância dos coeficientes de regressão (β) e distribuição gráfica. Dentre os modelos hipsométricos testados o que melhor se ajustou ao banco de dados, foi a equação de Prodan, com um coeficiente de determinação (R^2) de 0,89, enquanto que para os modelos volumétricos o melhor resultado foi encontrado através do modelo de Meyer, com um coeficiente de determinação (R^2) de 0,99. Todos os modelos avaliados foram eficientes para estimar a altura e o volume do sistema Integração Lavoura-Floresta (ILF), demostrando com isso que o eucalipto GG100 é uma boa opção em sistemas integrados.
Palavras-chave: Eucalipto; Madeira; Modelagem; Recursos renováveis.

Abstract

Due to the positive impact that the eucalyptus species has on the Brazilian economy, it is currently the most used forest essence. The objective of this work was to evaluate different hypsometric and volumetric models for *Eucalyptus urograndis* clones (*Eucalyptus urophylla* S.T. Blak and *Eucalyptus grandis* W. Hill ex Maiden) in a Crop-Forest Integration (CFI) system. The trees were evaluated at 7 years of age and arranged in double rows, occupying 20.76% of the total system area. The individuals were subjected to rigorous volumetric cubing according to the Smalian method at intervals of one meter up to full height. The following models were evaluated for the collected height data: Linear, Trorey, Stofels, Curtis, Henriksen, Prodan, Chapman & Richards, Petterson and Bailey & Clutter. Furthermore, the Spurr, Hohenald-Krenn, Stoate, Schumacher Hall, Meyer, Husch, Ogaya and Takata models were used for volume data. The results were determined through the coefficient of determination (R^2), standard error of the estimate in percentage (Syx%), significance of the regression coefficients (β) and graphical distribution. The hypsometric model which best fit the database among tested models was the Prodan equation, with a coefficient of determination (R^2) of 0.89, while the best result for volumetric models was found using the Meyer model, with a coefficient of determination (R^2) of 0.99. All evaluated models were efficient in estimating the height and volume of the Crop-Forest Integration (CFI) system, thus demonstrating that GG100 eucalyptus is a good option in integrated systems.
Keywords: Eucalyptus; Wood; Modeling; Renewable resources.

INTRODUCTION

Eucalyptus is the forest essence which best meets the needs of the forestry sector due to its high productivity, rapid growth, employability and diversity of its products and the positive impact that the species has on the Brazilian economy, and therefore it is currently the most used (VIANA *et al.*, 2016). Thus, integrated systems emerged in order to expand its production, consisting of an association of annual and perennial crops in the same area (VENTURIN *et al.*, 2013). The main purpose of these systems is to increase economic growth and minimize the negative impacts that agricultural production causes to natural ecosystems (PACIULLO *et al.*, 2011).

Studies referring to these areas are necessary to provide a foundation to expand notions about the components inserted in this environment, especially with regard to species with long cycles due to the lack of information. In addition, it is noteworthy that the Southeast region of Brazil is prominent in the agricultural sector, but because of the growing demand for food, it is necessary to find a balance between environmental conservation and productivity. It is important to implement and conduct new integrated system areas so that agricultural production can grow sustainably together with the forestry sector in order to foster the Brazilian economy, so that it operates consciously to meet the demands of present and future generations.

Thus, it is essential to study the biometric characteristics that are directly related to forest development and production to obtain knowledge about the forest resources inserted in these systems, thereby providing elements for the rational ordering of products. Tree height is an important dendrometric variable for estimating the volume and increment of wood, being a necessary characteristic in identifying the quality of site indices (LUNDGREN; SILVA; FERREIRA, 2015). However, its measurement through instruments is a procedure that requires a long time (when compared to measuring the diameter), financial resources, and is subject to several errors from operator mistakes to device inaccuracies (SOUSA *et al.*, 2013). In this context, the use of hypsometric relationships is an important tool, as it is possible to predict the height of others by measuring only a few individuals, saving time in the field (MANFREDI *et al.*, 2013).

Diameter is an essential variable for volumetric quantification, biomass assessment and studies related to growth. It is the most used measure to serve as a basis for many calculations, also enabling to obtain results on the density of the forest in terms of basal area (CUNHA, 2004). Furthermore, it is possible to obtain the volume through evaluating these variables, which is the most important characteristic to acquire results and projections of forest products.

Thus, the hypsometric and volumetric relationships make it possible to make choices about various types of interventions mainly related to forest management, which are only possible through fitting statistical models (SALES *et al.*, 2012). It is possible to predict the productive potential of different regions and compartments through these equations, and help optimize the use of resources aimed at forest production and environmental protection, making it possible to estimate a variable that is difficult to measure through one that is easy to measure (VIANA *et al.*, 2016).

Given the above, the objective of this work was to evaluate different hypsometric and volumetric models for *Eucalyptus urograndis* clones (*Eucalyptus urophylla* ST Blak and *Eucalyptus grandis* W. Hill ex Maiden) in a Crop-Forest Integration (CFI) system in the southeast region of the state of Goiás in order to analyze the following scientific hypotheses:
Hypothesis 1: The fitted models for hypsometric and volumetric relationship portray the system in such a way that all the statistical fitting criteria present results considered to be high;
Hypothesis 2: The fitted models do not portray the forest component inserted in the Crop-Forest Integration (CFI) system.

MATERIAL AND METHODS

Characterization of the experimental area

The experiment was conducted in the city of Ipameri, Goiás, with geographic coordinates; 17º 43' 19" latitude S and 48º 09' 35" longitude W; and altitude of 764 m. The region's climate is classified as Aw (seasonal tropical) with an average annual rainfall of 1,600 mm and an average temperature of 23ºC (ALVARES *et al.*, 2013). Soil sample collections were performed at a depth of 0-20 cm to set up the experiment, and then submitted to evaluate the chemical characteristics.

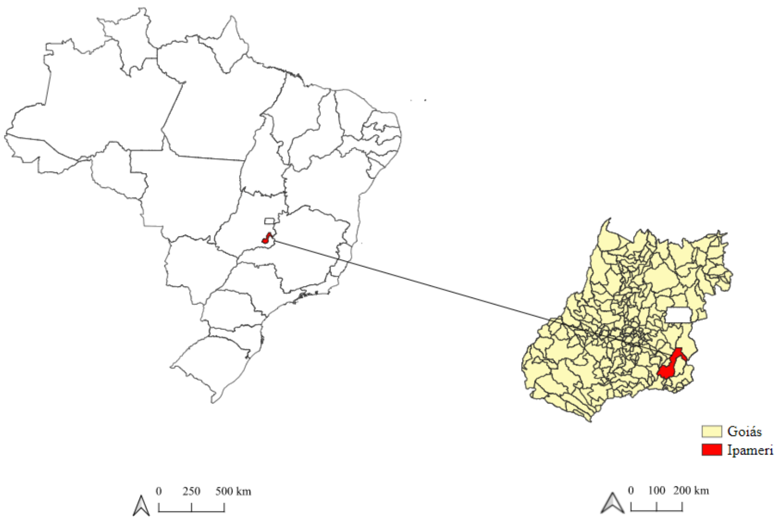

Figure 1: Location of the experimental area of the study in the southeast region of the state of Goiás.
Figura 1: Localização da área experimental do estudo na região sudeste do estado de Goiás.

The soil in the area is classified as dystrophic Red-Yellow Latosol, with a sandy texture and flat topography (EMBRAPA, 2018). The results among the eucalyptus rows presented the following characteristics: P

Melich = 3 g.dm^{-3}; organic matter (O.M.) = 20 g.dm^{-3}; K^+ = 0,11; Ca^{2+} = 1.6; Mg^{2+} = 0.6; Al^{3+} = 0; H+Al = 1.7; CEC = 4.5 cmol$_c$.dm^{-3}.

Experiment installation

The experimental area consisted of a Crop-Forest Integration (CFI) system in the East-West direction. The tree component was planted with *Eucalyptus urograndis* hybrid clones (GG100) in 2010 in an area of one hectare (ha). The ants in the experimental area and adjacent regions were controlled to plant the culture, and later holes were drilled and fertilized with 120 grams of NPK 06-30-10. The trees were arranged in double rows (3 m x 2 m x 17 m), totaling 346 individuals and occupying 20.76% of the total system area.

Soybean crops were planted between the rows (*Glycine max* (L.) Merr.), sown in a single crop respecting one meter on each side from the arboreal component line, in 2015, 2016 and 2017. Fertilization was performed for planting on the basis of 300 kg/ha of the formula 02-28-18.

Data collection

Information on the characteristics of the stand was determined through a forest census carried out in 2016 by measuring the diameter at breast height (DBH) at 1.30 meters from the ground and height of all trees in the system using a bevel gauge and a Haglof electronic inclinometer, respectively.

The dendrometric data of individuals was collected in 2017 at the age of seven in the culture cycle. The trees were distributed into five diameter classes based on the analysis of the census carried out in 2016, through which three individuals in each class were slaughtered, totaling 15 trees. The trees were subjected to rigorous volumetric cubing to obtain the volume according to the Smalian method and described by Finger (1992) with a bevel gauge. The sampling positions that determined the diameters were: 0.10 m, 0.30 m, 1.30 m, 2.30 m and so on, at intervals of one meter until total height. The trunk was sectioned into 1 m long short logs up to the point where the diameter reached 7 cm (commercial diameter). A diameter of 3 cm was considered as the tip of the trees after that point, and 3 cm to the apex was considered as a branch.

Hypsometric model fittings

The 15 individuals used in the rigorous volumetric cubing were used to estimate the height of the component by using the diameter at breast height (DBH) and the total height (h) as variables. Different linear and non-linear hypsometric models found in the literature were tested in order to identify the most suitable for the CFI system. Thus, nine equations were chosen from among these in order to analyze which provided the best fit (Table 2).

Table 1: Hypsometric models used to estimate height in *Eucalyptus urograndis* CFI system in Ipameri, Goiás, Brazil.

Tabela 1: Modelos hipsométricos utilizados para estimativa da altura em sistema ILF de *Eucalyptus urograndis* em Ipameri, Goiás, Brasil.

Author	Models
Linear	$h_i = β0 + β1 * d + \mathcal{E}i$
Trorey	$h = β0 + β1 * d + β2 * d^2 + \mathcal{E}$
Stofells	$lnh = β0 + β1 * lnd + \mathcal{E}$
Curtis	$lnh = β0 + β1 * 1/d + \mathcal{E}$
Henriksen	$h = β0 + β1 * lnd + \mathcal{E}$
Prodan	$h = \frac{d^2}{β0 + β1 * d + β2 * d^2} + \mathcal{E}$
Chapmam & Richards	$h = β0 * (1 - e^{β1*d})^{β2} + \mathcal{E}$
Petterson	$h = \frac{1}{(β0 + \frac{β1}{d})^3} + \mathcal{E}$
Bailey & Clutter	$lnh = β0 – (β1 * (\frac{1}{d})^{β2} + \mathcal{E}$

In which: 1n = natural logarithm; h = total height (m); d = diameter at breast height (cm); β0, β1 and β2 = regression coefficients; E = random error.

Volumetric model fittings

From the volume data obtained by the Smalian expression for the traditional cubing method, linear and non-linear volumetric models were used to estimate the wood volume of the integrated system (Table 3).

Table 2: Volumetric models used to estimate the volume in *Eucalyptus urograndis* CFI system in Ipameri, Goiás, Brazil.

Tabela 2: Modelos volumétricos utilizados para estimativa do volume em sistema ILF de *Eucalyptus urograndis* em Ipameri, Goiás, Brasil.

Author	Models
Suprr (linear simples)	$v_i = \beta0 + \beta1 * d^2 * h + \mathcal{E}i$
Hohenadl-Krenn	$v = \beta0 + \beta1 * d + \beta2 * d^2 + \mathcal{E}$
Stoate	$v = \beta0 + \beta1 * d^2 + \beta2 * (d^2 * h) + \beta3 * h + \mathcal{E}$
Schumacher & Hall	$lnv = \beta0 + \beta1 * lnd + \beta2 * lnh + \mathcal{E}$
Meyer	$v = \beta0 + \beta1 * d + \beta2 * d^2 + \beta3 * (d * h) + \beta4 * (d^2 * h) + \mathcal{E}$
Husch	$lnv = \beta0 + \beta1 lnd + \mathcal{E}$
Ogaya	$v = d^2 * (\beta0 + \beta1 * h) + \mathcal{E}$
Takata	$v = \frac{d^2 h}{\beta0 + \beta1 d} + \mathcal{E}$

In which: v = volume; d = diameter at breast height; h = total height (m); β0, β1 and β2, β3 = regression coefficients; ln = natural logarithm; E = random error.

Evaluation criteria of the models

The fitting of linear and non-linear models was performed using the Microsoft Office Excel 2010® software program. The goodness-of-fit of the models was evaluated based on the following statistical fit criteria: coefficient of determination (R^2) (Equation 1), standard error of the estimate in percentage (Syx%) (Equation 2) and significance of the regression coefficients (β) (MACHADO *et al.*, 2008). Even though the statistical fitting criteria are efficient for choosing the best model, it is considered an indispensable factor for the graphical analysis of the residuals (Equation 3), as it enables identifying whether or not there is bias in the estimation of the dependent variable along the regression line or if there is homogeneity of variance, with this resource being decisive in assessing the quality of the model (SALES *et al.*, 2012). In addition, graphical analyzes of dendrometric characteristics were performed to verify the correlation between the observed and estimated data.

$$R^2 = 1 - \frac{SQres}{SQtot} \quad (1) \qquad Syx = \sqrt{\frac{SQres}{n-p}} \quad (2) \qquad Res\% = \left(\frac{y_i - \hat{y}_i}{y_i}\right) x\ 100 \quad (3)$$

In which: yi = dependent variable observed in the i-th tree; ŷi= estimate of the dependent variable in the i-th tree; p = number of model coefficients; n = number of observations; SQres = sum of residual squares; SQtot = total sum of squares.

RESULTS

Determination of hypsometric models

The table below shows the coefficients and the fit statistics of the models. The coefficient of determination (R^2) ranged from 0.72 to 0.89 to estimate the height variable as a function of diameter. The Prodan model presented more accurate statistics with a coefficient of determination (R^2) of 0.89, standard error of estimation in percentage (Syx%) of 15.60 and a calculated F of 7.74 (Table 4).

Table 3: Adjustments of the hypsometric models attributed to *Eucalyptus urograndis* planting in the CFI system.
Tabela 3: Ajustes dos modelos hipsométricos atribuídos ao plantio de *Eucalyptus urograndis* em sistema ILF.

Author	Parameters			R^2	Syx (%)	F
	β0	β1	β2			
Linear	-8.01	1.49*	-	0.77	17.15	43.87
Trorey	-31.91	3.85	-0.05	0.79	17.04	22.80
Stofels	-1.27	1.44*	-	0.75	0.85	39.19
Curtis	4.50	-28.25*	-	0.74	0.86	38.17
Heriksen	-70.14	31.00*	-	0.78	16.73	46.81
Prodan	45.78*	-3.05*	0.08*	0.89	15.60	4.74
Chapmam & Richards	321.83*	-0.008*	1.43*	0.72	17.37	1.37
Petterson	0.19*	3.23*	-	0.74	16.88	4.04
Bailey & Clutter	4.55*	29.58*	0.96*	0.73	6.62	1.36

In which: (β): Estimated coefficients, (R^2): Coefficient of determination, (Syx%): Relative standard error and (F): Calculated F value.
* significant values for the coefficients (p≤ 0..05).

The coefficients were statistically significant at the analyzed probability level, proving that the independent variable is directly related to the dependent variable. All models satisfactorily fit according to the database, showing great similarity. However, Prodan's model fit better and portrayed the distribution of points more adequately around the midline, providing greater correlation between observed height and estimated height around the regression line (Figure 2).

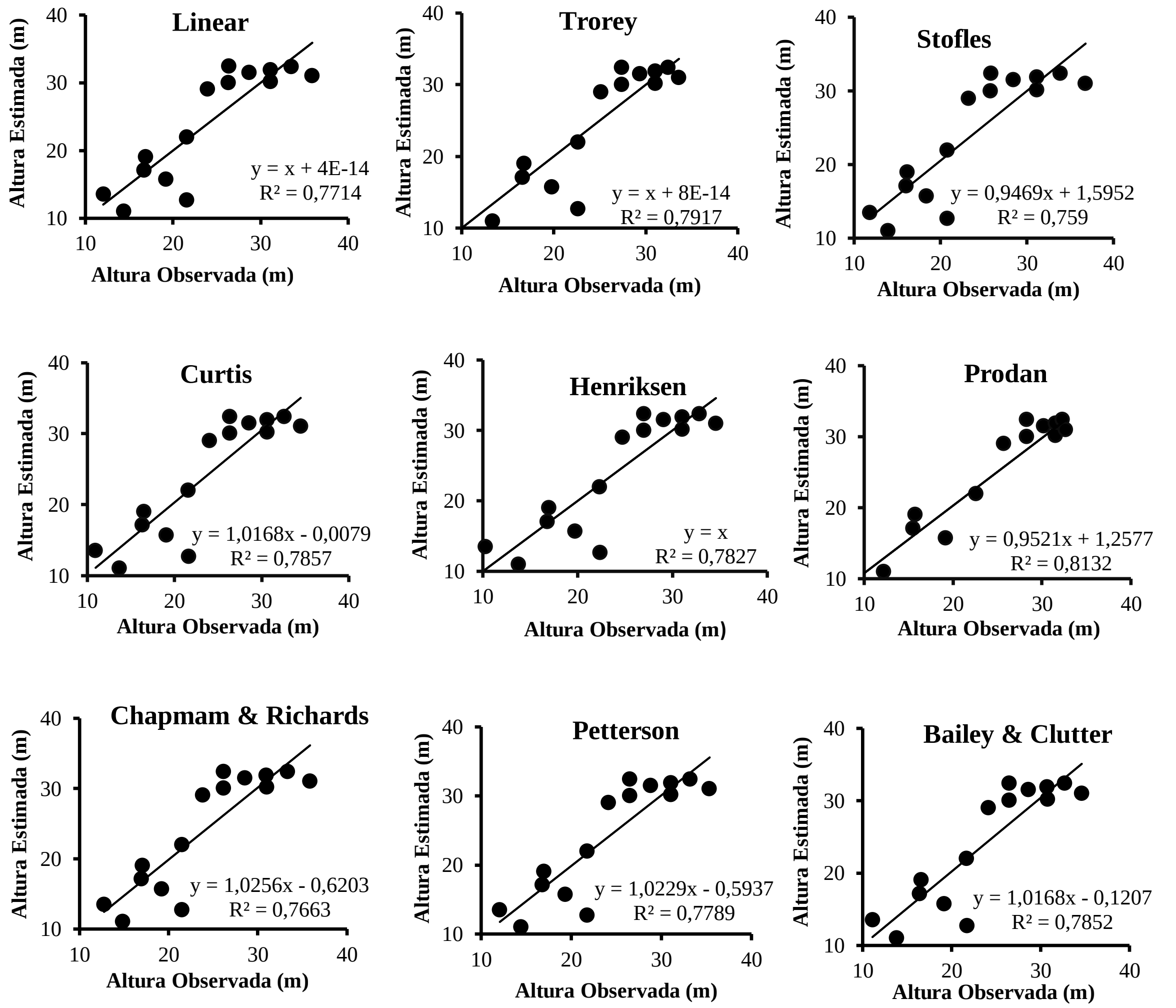

Figure 2: Correlation between estimated height and observed height of the hypsometric models tested for *Eucalyptus urgrandis*.

Figura 2: Correlação entre altura estimada e altura observada dos modelos hipsométricos testados para o *Eucalyptus urograndis.*

Determination of the volumetric models

It was possible to verify through statistical tests that the results of the models showed high correlation. This demonstrates that there was a relationship between the dependent variable and the independent variables. All coefficients of determination (R^2) presented a value greater than 0.81, with emphasis on the Meyer model, which had an R^2 of 0.99 and Sxy (%) of 6.66 (Table 5), being considered the most suitable for estimating the wood volume of the integrated system.

Table 4: Adjustments of volumetric models attributed to *Eucalyptus urgrandis* planting in the CFI system.
Tabela 4: Ajustes dos modelos volumétricos atribuídos ao plantio de *Eucalyptus urgrandis* em sistema ILF.

Author	Parameters					R²	Syx(%)	F
	β0	β1	β2	β3	β4			
Suprr	0.04	0.006*	-	-	-	0.89	22.83	108.25
Hohenadl-Krenn	-2.33	-0.19	-0.018	-	-	0.87	26.05	40.54
Stoate	0.07	0.43*	0.01	0.01	-	0.97	12.30	135.44

Schumacher Hall	-10.77	-2.47*	0.90*	-	-	0.92	30.72	79.45
Meyer	-0.85*	0.05*	0.41	0.01*	0.01*	0.99	6.66	353.21
Husch	-11.91*	3.78	-	-	-	0.89	36.20	110.07
Ogaya	14.35*	0.01*	0.01*	-	-	0.81	25.23	1.22
Takata	13.58*	6684.29*	311.76*	-	-	0.81	20.85	1.23

In which: (β): Estimated coefficients, (R^2): Coefficient of determination, (Syx%): Relative standard error and (F): Calculated F value.
* significant values for the coefficients (p≤ 0.05).

It can be noted that all models tested showed a positive correlation in analyzing the results of the correlation between observed volume and estimated volume (Figure 2), indicating that the mathematical equations adequately explain the relationship between height (h) versus diameter (DBH) of the system. However, the Meyer model showed a more homogeneous distribution of residuals around the regression line.

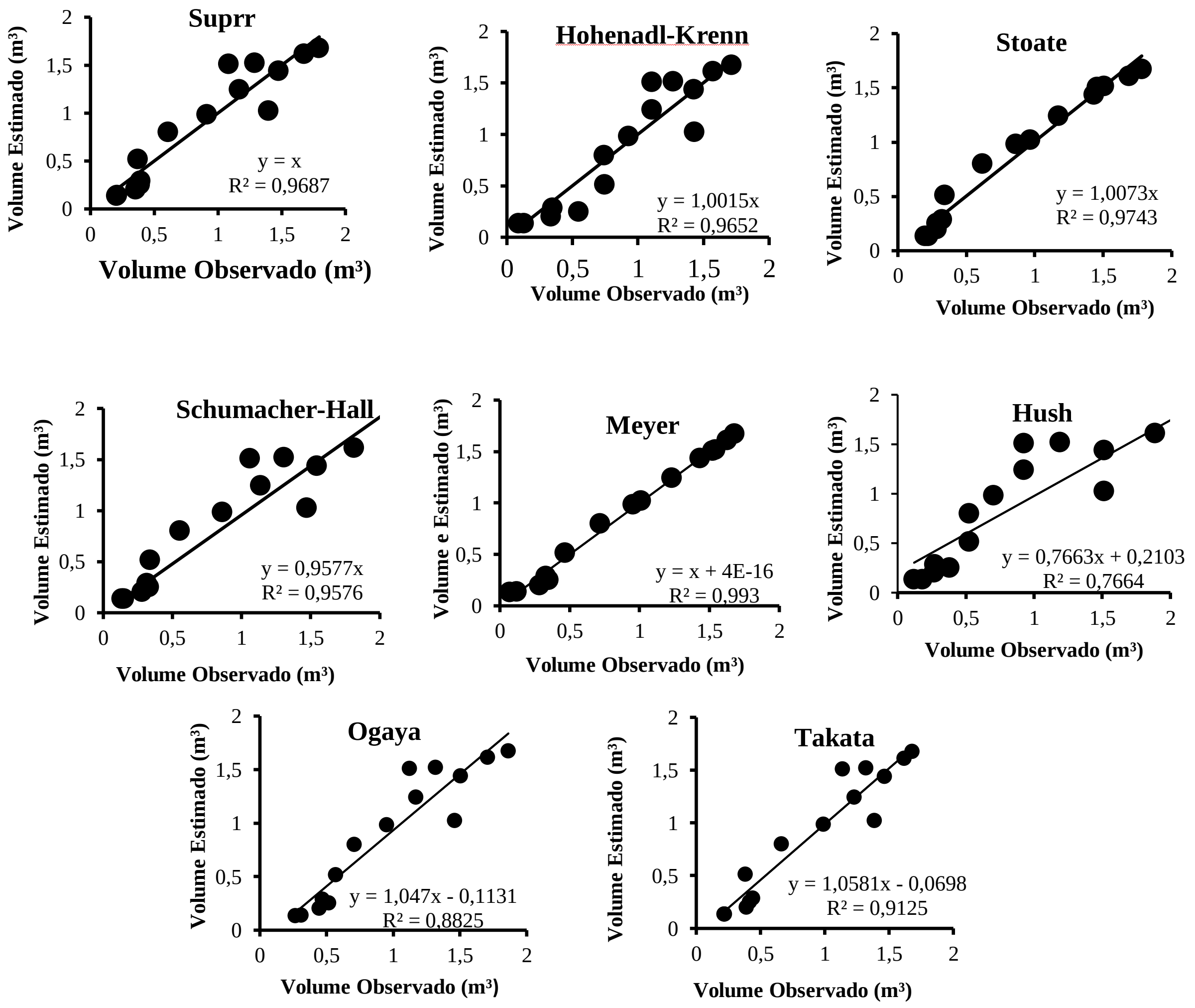

Figure 3: Correlation between observed volume and estimated volume for the volumetric models tested for *Eucalyptus urgrandis*.
Figura 3: Correlação entre volume observado e volume estimado dos modelos volumétricos testados para o *Eucalyptus urograndis.*

The residual scatter plot of the two best tested hypsometric and volumetric models is shown in Figure 3, confirming that the data were homogeneous and without trends along the regression line, indicating that the equations met the assumption of independence of the residuals.

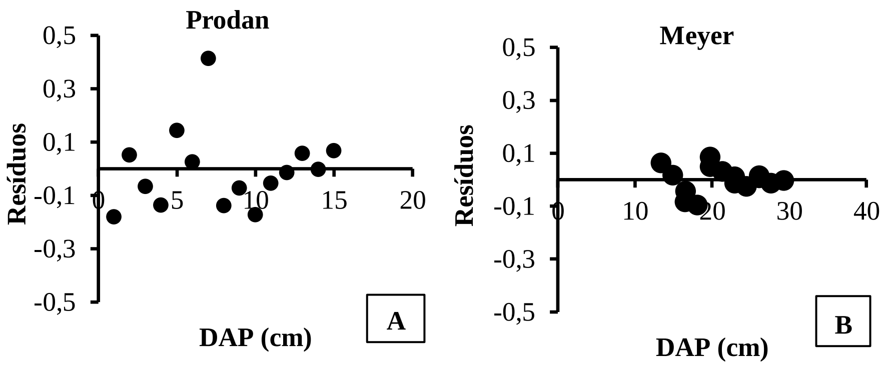

Figure 4: (A) Residue dispersion plot of the best fitted hypsometric model to *Eucalyptus urgrandis*; (B) Residue dispersion graph of the best fitted volumetric model of *Eucalyptus urgrandis* in the CFI system, in Ipameri, Goiás, Brazil.

Figura 4: (A) Gráfico de dispersão de resíduos do melhor modelo hipsométrico ajustados ao *Eucalyptus urgrandis*; (B) Gráfico de dispersão de resíduos do melhor modelo volumétrico ajustado do *Eucalyptus urgrandis* em sistema ILF, em Ipameri, Goiás, Brasil.

DISCUSSION

All models evaluated herein presented a coefficient of determination greater than 0.7, highlighting the Prodan model, which resulted in the best values of the analyzed statistics with an R^2 value of 0.89. According to Scolforo (1998), it is common that the value of R^2 does not exceed 0.8 when dealing with hypsometric relationships, since the height/diameter correlation is not as strong as the height/volume of trees, thus explaining the R^2 value found in most works related to height fits in models. However, the coefficient of determination value presents results above 0.8 in most studies related to integrated systems. In the work carried out by Moraes Neto *et al.* (2010) analyzing different fits of hypsometric models in an agroforestry system for two eucalyptus clones, one with *Eucalyptus cloeziana* containing 947 trees and the other with *Eucalyptus urograndis* with 1,559 individuals, both at 18 months of age, they found coefficient of determination values fitting between 32% to 88%. Also in the study by Ilario *et al.* (2018) evaluating *Eucalyptus grandis* in a Crop-Livestock-Forest Integration system at eight years of age, it was possible to find R^2 values similar to those analyzed in the present study, ranging from 0.89 to 0.90. Therefore, it is worth noting that height is a dendrormetric variable that is directly related to the quality of the site, and it can be inferred from such results that the integrated system is a positive factor that leads species to develop satisfactorily, and obtain productivity more sustainably.

Corroborating the results explained, Viana *et al.* (2016), analyzed four models (Linear, Trorey, Stofells and Curtis) for I144 clone stands in Bahia, Brazil. The best value was obtained through the Stofells equation with an R^2 of 59.5% and a Syx of 8.23%, and this result compared to the statistical criterion obtained in the present study was less than 0.29%. Therefore, the statistics found in studies related to the integrated system are considerable, thus confirming how much the intercropped species present synergism and favors forest growth.

In analyzing three different volumetric models for *Eucalyptus grandis* in a Crop-Livestock-Forest Integration (CLFI) system in the state of Paraná, Ilario *et al.* (2018) found an R^2 value of 0.99, constituting a similar result to that obtained through the Meyer equation in the integrated system in question. Likewise, a study by Cerqueira *et al.* (2020) analyzing *Eucalyptus grandis* x *Eucalyptus urophylla* at 51 months of age in a Crop-Livestock-Forest Integration system (CLFI) in the Mato Grosso region found coefficient of determination values of 0.98. This infers that integrated systems present high values, indicating that wood productivity, the ultimate goal of forest products, is significant. After all, diametric growth is directly related to the increase in planting spacing, as occurs in intercropping systems. Thus, greater spacing benefits diameter growth of trees, an important factor for obtaining stems with greater increments, and with greater added value such as wood production for furniture and sawmills (MAGALHÃES *et al.*, 2005; OLIVEIRA *et al.*, 2009), demonstrating the importance of its implementation and new studies to promote the agricultural sector.

It can be noted from the results of the correlation between observed volume and estimated volume that all of the tested models showed a positive correlation, but the Meyer model showed a more homogeneous distribution of residues. This is because in an area of one hectare with a spacing of 3 m x 2 m x 17 m, a wood volume of 328.58 m^3 was estimated according to the Smalian method. The volume values per hectare in this study differ from the results found by Oliveira *et al.* (2015) in a Crop-Livestock-Forest Integration System (CLFI) analyzing the intercropping of acacia and eucalyptus, with three rows of six plants every 10 m, and with a spacing between plants of two meters between trees at 25 months of age, in which the authors found volume values of 29.82 $m^3.ha^{-1}$. Therefore, it could be seen that *Eucalyptus urograndis* (GG100) presents satisfactory results in integrated production systems, and the Meyer equation was selected to estimate the volumetry, and it can also be used to estimate the volume of *Eucalyptus urograndis* with structural characteristics similar to the present study.

However, it is noteworthy that there are few studies carried out in the southeast region of Goiás, making the need for more studies evident and consequently gauging a larger number of trees in order to improve the estimates of the analyzed dendrometric characteristics. In addition, it is important to emphasize that the use of intercropping plantations has several advantages, among which is the use of leguminous trees in contributing to improve the system's production and with a reduction in the costs of chemical fertilizers when compared to monocultures subjected to fertilization with mineral nitrogen (OLIVEIRA *et al.*, 2015). As a result, this can help to minimize impacts and contribute to the sustainability of production systems.

CONCLUSION

- The hypsometric Prodan model and the volumetric Meyer model promoted more precise and accurate estimates among the models used, with coefficient of determination (R^2) values of 0.89 and 0.99 respectively.
- All statistical criteria were high, demonstrating that the hypsometric and volumetric model fittings well represent the database of the analyzed system.

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