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Volumetric models for quantifying the wood volume of two eucalyptus hybrids in an agrosilvipastoral system

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Abstract

Quantifying the wood volume of forest stands is essential for planning sustainable forest management. The most efficient means of quantifying wood volume is volumetric equations. Many models for adjusting volumetric equations have been developed and tested, but their suitability for agrosilvipastoral systems remains unclear. To address this gap, we assessed the ability of six volumetric models to generate estimates of the total volume with bark of eucalyptus hybrids Grancam 1277 and Urograndis H-13. The trees were cultivated in an agrosilvipastoral system in an Arenic Hapludult in the municipality of Votuporanga, São Paulo State, Brazil, which is within the Cerrado biome. For Urograndis H-13, the Takata model was most accurate for quantifying volume, as it gave the highest F test (178.38) and adjusted coefficient of determination (0.93) values and the smallest standard error (0.06). The nonlinear and linear Schumacher-Hall models were most accurate for Grancam 1277, as this model gave the highest F test (54.59) and adjusted coefficient of determination (0.8) values and the smallest standard error (0.07).

Keywords: agroforestry, crop systems, intercropping systems, other models, statistics.
Abbreviations: BS_base saturation; CBH_circumference at breast height; DBH_diameter at breast height; F_F test; R^2_coefficient of determination; r_coefficient of Pearson correlation

Introduction

The agriculture and livestock sector is undergoing major transformations in response to growing production costs and market competition and demands for increases in productivity, quality and profitability without harming the environment (Lemos-Junior et al., 2016). An appealing option for addressing global issues such as food security, climate change, sustainable farming, and societal conditions in rural areas is integrated agricultural production systems (Borges et al., 2019). These systems benefit farmers and society as a whole by maintaining soil fertility, which is critical for conserving natural resources and providing environmental services (Lemaire et al., 2014; Salton et al., 2014), and their implementation in the Brazilian Cerrado biome is increasing (Tonucci et al., 2017),

Agrosilvipastoral systems are a type of integrated agricultural production system in which different crop systems, such as grains, fibers, meat, milk, and agroenergy, are intercropped or cropped in sequence or rotation in the same area as trees (Macedo, 2009). The synergism between pastures and annual crops in agrosilvipastoral systems may improve the physical, chemical and biological properties of the soil; disrupt disease cycles; reduce insect pests and weeds; reduce economic risks through diversification of activities; and lower the costs of recovering and renovating degraded pastures (Vilela et al., 2011). However, the economic and environmental success of an agrosilvipastoral system depends on the correct management of the species and the production factors that affect those species (Melotto et al., 2009), including sustainable forest management plans for the utilization of its trees. Studies of biometric characteristics directly related to forest development and production are essential for understanding the forest resources in agrosilvipastoral systems (Cunha et al., 2022). The species of tree, pasture and crop used must be complementary in terms of their influences on nutrient cycling, light availability and microclimate (Lemos-Junior et al., 2016). In appropriately designed systems, the trees and pasture successfully interact to optimize the yields of both (Pezzopane et al., 2015). In Brazil, *Eucalyptus* is the most common tree species in agrosilvipastoral systems due to its high adaptability to various soil and climate conditions, vigorous growth, efficiency in the use of water and mineral resources, tolerance of low-fertility soils, low to moderate rates of infestation by pests, diseases and weeds, high productivity, rapid growth, product utility and diversity, and positive economic impact (Ferreira et al., 2016; Viana et al., 2016).

Wood volume quantification is an essential element of implementing sustainable forest management plans (Leite and Andrade, 2002) and optimally meeting the demand for certain forest products (Andrade et al., 2015). Reliably quantifying and forecasting wood stock is essential for managing forest enterprises (Cerqueira et al., 2020). To quantify the wood volume in a forest stand, a forest inventory of a sample is typically carried out, and the results are used to infer the parameters of the forest stand, such as the diameter, height, volume and number of trees per hectare (Machado et al., 2000). However, measuring the height of trees is an exhaustive and error-prone process. Alternatively, mathematical models can be used to predict the available forest volume for forestry planning and management for economic benefits and sustainability based on the growth, yield and quality of wood products (Ashraf et al., 2015; Bonete et al., 2016). In these models, hypsometric and volumetric equations are used to estimate volume from easy-to-obtain measurements, such as the diameter at breast height (DBH) (Parent and Moore, 2003; Azevedo et al., 2011), which is related to the height of individuals and volume in agrosilvipastoral systems (Abrantes et al., 2019). The use of volumetric equations is the most efficient procedure for quantifying the volume production of a forest stand (Guimarães and Leite, 1996). However, volumetric equations must be adjusted based on the real volume to relate volume to the diameter and height of the trees, which requires the felling of a sample of trees through a process known as cubage. Cubage allows the determination of the diameter distribution of the population where a volumetric equation is to be applied (Couto et al., 1989; Andrade and Schmitt, 2018).

Choosing appropriate equations is critical for forestry inventory work, since any trend error in estimating the volume per tree will impact the population estimate, resulting in an under- or overestimation of production (Campos et al., 1985). Many models for adjusting volume equations have been developed and tested (Couto and Bastos, 1987; Machado et al., 2002; Tewari and Kumar, 2003; Scolforo et al., 2004; Nunes et al., 2005). Although the efficiency of these models has been established, none provides superior performance for all species and conditions, and thus testing several volumetric models through statistical analysis is always recommended to identify the best model for each case (Machado et al., 2002; Thomas et al., 2006; Moraes Neto, 2009; Andrade, 2017; Cruz et al., 2019). Moreover, the applicability of these models to agrosilvipastoral systems remains unclear. To address this gap, the present study compared the ability of six volumetric models to generate estimates of the total volume with bark of two eucalyptus hybrids, Urograndis H-13 and Grancam 1277, cultivated in an agrosilvipastoral system.

Results

Tables 1 and 2 provide the values of the f test, coefficient of determination, and standard error from the regression analysis of the tested models of volume with bark for eucalyptus hybrids Urograndis H-13 (Table 1) and Grancam 1277 (Table 2).

The graphs of the residuals of the tested models for eucalyptus hybrids Urograndis H-13 and Grancam 1277 are shown in Figures 1 and 2, respectively. The graphical analysis of residuals indicates whether there is bias in the distributions, which can lead to underestimation or overestimation of volume and thus is an important consideration in choosing the best model (Cruz et al., 2019). The coefficients of determination of the tested models of volume with bark ranged from 0.9 (model 3) to 0.93 (model 6) for eucalyptus hybrid Urograndis H-13 and from 0.77 (model 4) to 0.80 (models 1 and 5) for eucalyptus hybrid Grancam 1277.

For models 1, 2, 3, 4, 5, and 6, the estimated average volumes with bark per tree were 0.7119, 0.7119, 0.7120, 0.7163, 0.7120, and 0.6981 m^3 $tree^{-1}$ for Urograndis H-13 and 0.6589, 0.6588, 0.6591, 0.6634, 0.6589, and 0.6524 m^3 $tree^{-1}$ for Grancam 1277, respectively. The total estimated average volumes with bark per hectare were 263.4123, 263.3970, 263.4335, 265.0178, 263.4282, and 258.3008 m^3 for Urograndis H-13 and 243.8025, 243.7483, 243.8497, 245.4584, 243.7972, and 241.3781 m^3 ha^{-1} for Grancam 1277, respectively. For the estimates of shelled volume, the residuals were closest to the central axis for model 6 for Urograndis H-13 and models 1 and 5 for Grancam 1277.

The graphs of the observed volume × estimated volume of the tested models for eucalyptus hybrids Urograndis H-13 and Grancam 1277 are shown in Figures 3 and 4, respectively. The coefficients of the Pearson correlation (r) for Urograndis H-13 were 0.9714, 0.9721, 0.9608, 0.9636, 0.9714 and 0.9726 for models 1, 2, 3, 4, 5, and 6, respectively. For Grancam 1277, the r values were 0.9627, 0.9547, 0.9759, 0.9752, 0.9627 and 0.9422 for models 1, 2, 3, 4, 5, and 6, respectively.

Discussion

Because overestimating or underestimating the volume of wood in an enterprise can compromise decision-making (Salles et al., 2012), it is important to choose the most appropriate model for the edaphoclimatic conditions of the specific agrosilvipastoral system to assess the economic viability of the system.

For eucalyptus hybrid Urograndis H-13, the coefficients of determination of the volumetric models corroborated the results of Santana et al. (2005), Thomas et al. (2006), and Azevedo et al. (2011). Of the six equations tested, the Takata equation (Model 6) provided the best adjustment of volume with bark for hybrid Urograndis H-13, with higher F and adjusted coefficient of determination (0.93) values and the smallest standard error (0.06). Abrantes et al. (2019) previously found that the Takata nonlinear model estimated the individual volume of wood with bark of hybrid Urograndis H-13 with greater accuracy in two agrosilvipastoral systems in Campo Grande, Mato Grosso do Sul, Brazil. Freitas and Andrade (2017) also determined that the Takata model was the most suitable for cubage of young trees of *Corymbia citriodora* with the aim of adjusting volumetric models for 49 months of age in Gurupi, Tocantins, Brazil. By contrast, Cunha et al. (2022) observed that the best volumetric model for *Eucalyptus* Urograndis GG100 in an agrosilvipastoral system in Ipameri, Goiás, Brazil, was the Meyer model, with a coefficient of determination of 0.99. Cerqueira et al. (2020) showed that the Schumacher-Hall nonlinear model was suitable for estimating the volume of *Eucalyptus* Urograndis trees planted in different arrangements and spacings in an agrosilvipastoral system in Sinop, Mato Grosso, Brazil. Similarly, Andrade (2017) found that the Schumacher-Hall model was the best model for assessing *Eucalyptus* Urograndis aged between 5 and 7 years in northeastern Bahia, Brazil.

For hybrid Grancam 1277, the nonlinear (Model 1) and linear (Model 5) Schumacher-Hall equations provided higher F and adjusted coefficient of determination (0.8) values and the smallest standard error (0.07). Santana et al. (2021) reported that the Schumacher-Hall model was the best adjusted volumetric model for *Eucalyptus* GG-100, with a coefficient of determination of 0.88. Bonete et al. (2016) observed that the coefficient of determination of the Schumacher-Hall adjusted volumetric model ranged from 0.96 to 0.98 for *E. benthamii*.

Table 1. Fitting statistics for the tested models of volume with bark for eucalyptus hybrid Urograndis H-13, 2016.

Model	F†	R^2‡	Standard error
1	171.12	0.92	0.07
2	175.73	0.93	0.07
3	126.92	0.9	0.09
4	133.03	0.9	0.08
5	171.12	0.92	0.07
6	178.38	0.93	0.06

†F: F test. ‡R^2: determination coefficient.

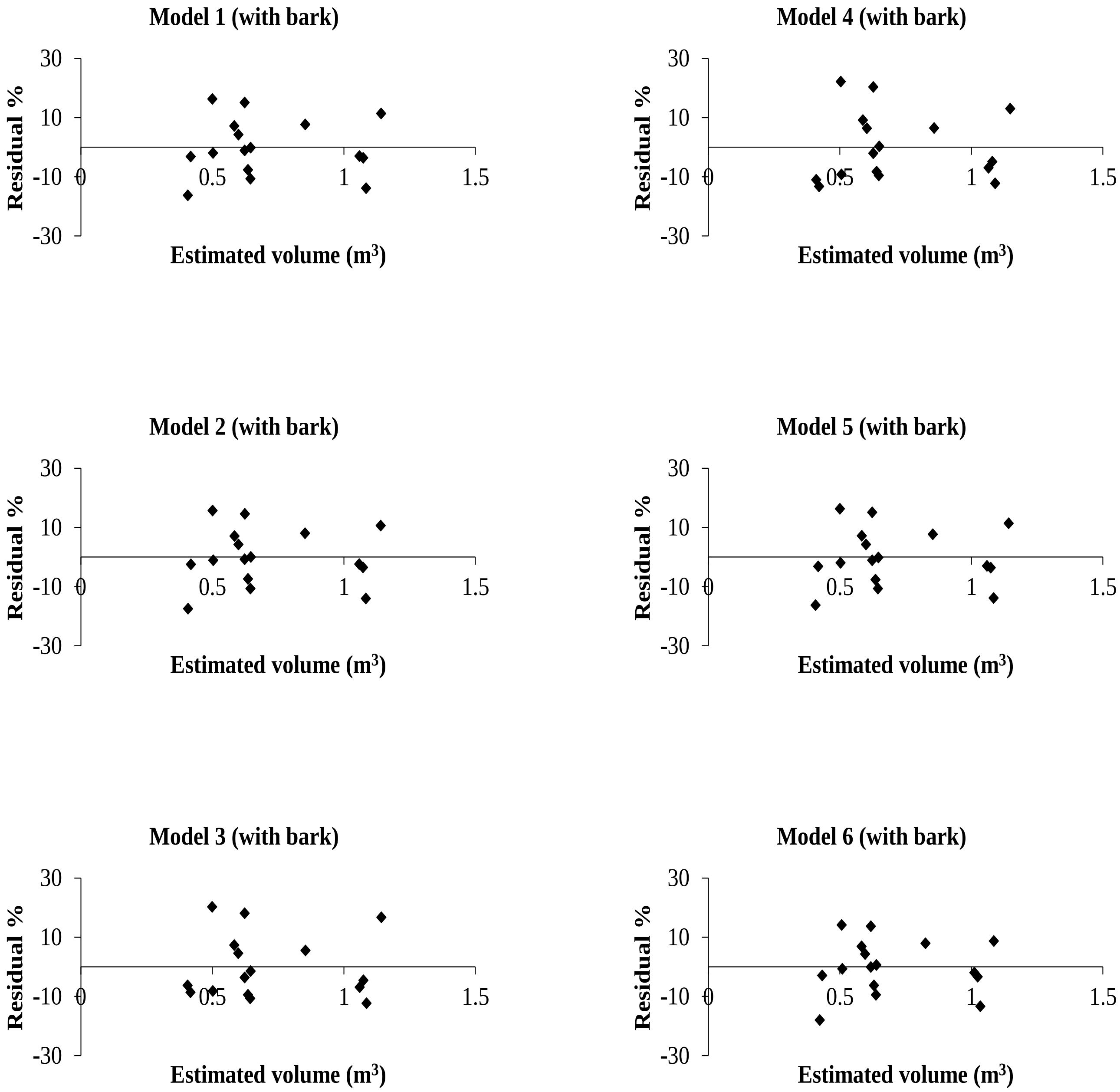

Figure 1. Percentage residuals of the estimated volume with bark of the tested models for eucalyptus hybrid Urograndis H-13, 2016: Model 1: $V = \beta_0.DBH^{\beta 1}.H^{\beta 2} + \varepsilon$ (nonlinear – Schumacher-Hall), Model 2: $\ln (V) = \beta_0 + \beta_1.\ln (DBH^2.H) + \varepsilon$ (Spurr), Model 3: $\ln (V) = \beta_0 + \beta_1.\ln (DBH) + \varepsilon$ (Husch), Model 4: $V = \beta_0 + \beta_1.DBH + \beta_2.DBH^2 + \varepsilon$ (Horenad and Krenn), Model 5: $\ln (V) = \beta_0 + \beta_1.\ln (DBH) + \beta_2.\ln (H) + \varepsilon$ (linear – Schumacher-Hall, 1933) and Model 6: $V = (DBH^2.H)/\beta_0 + \beta_1.DBH + \varepsilon$ (Takata).

Table 2. Fitting statistics for the tested models of volume with bark for eucalyptus hybrid Grancam 1277, 2016.

Model	F†	R²‡	Standard error
1	54.59	0.8	0.07
2	54.16	0.79	0.07
3	48.15	0.77	0.08
4	48.09	0.77	0.08
5	54.59	0.8	0.07
6	51.67	0.79	0.07

†F: F test. ‡R^2: determination coefficient.

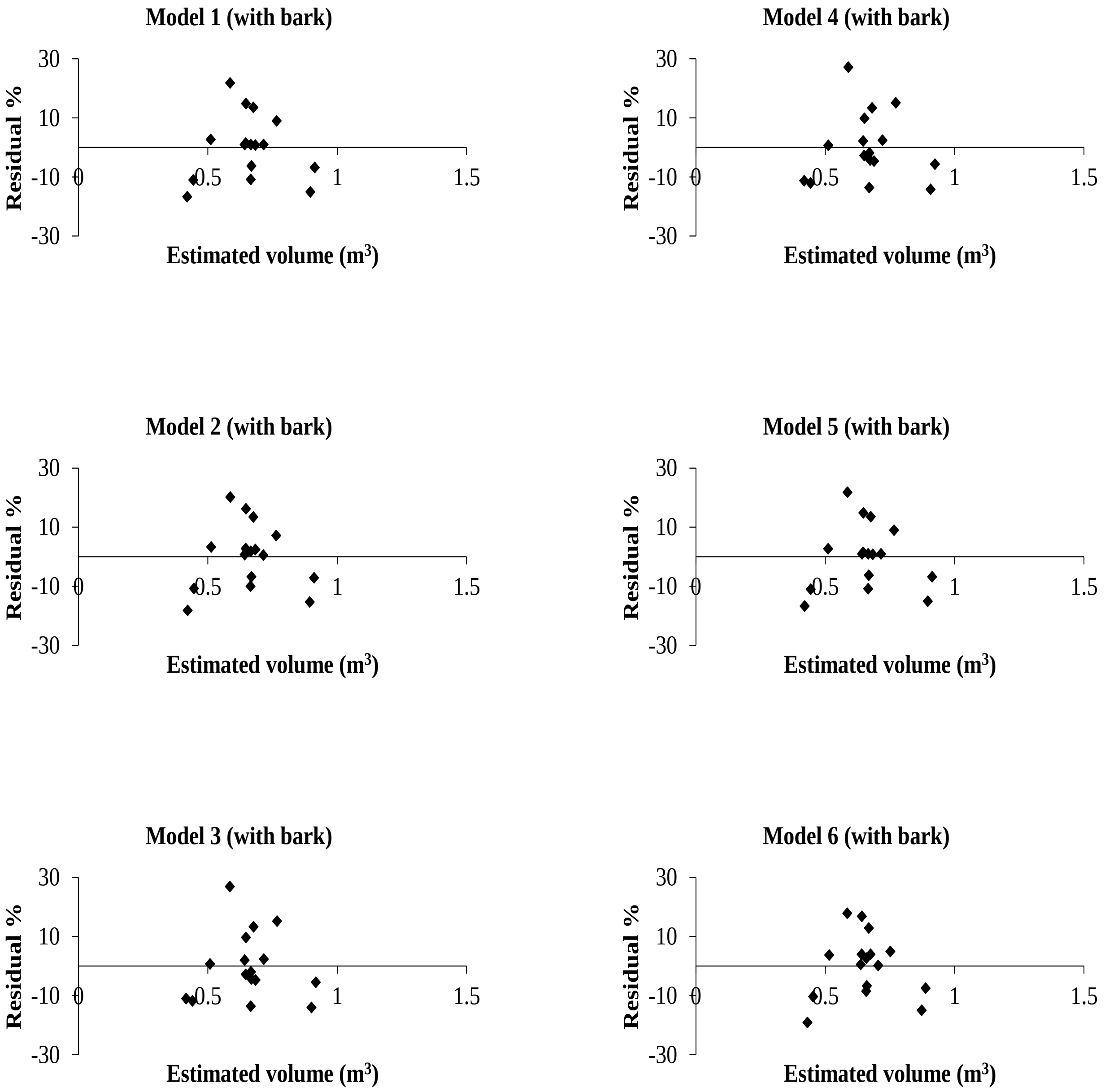
Model 1 (with bark)
Model 4 (with bark)
Model 2 (with bark)
Model 5 (with bark)
Model 3 (with bark)
Model 6 (with bark)

Figure 2. Percentage residuals of the estimated volume with bark of the tested models for the eucalyptus hybrid Grancam 1277, 2016: Model 1: $V = \beta_0.DBH^{\beta_1}.H^{\beta_2} + \varepsilon$ (nonlinear – Schumacher-Hall), Model 2: $\ln (V) = \beta_0 + \beta_1.\ln (DBH^2.H) + \varepsilon$ (Spurr), Model 3: $\ln (V) = \beta_0 + \beta_1.\ln (DBH) + \varepsilon$ (Husch), Model 4: $V = \beta_0 + \beta_1.DBH + \beta_2.DBH^2 + \varepsilon$ (Horenad and Krenn), Model 5: $\ln (V) = \beta_0 + \beta_1.\ln (DBH) + \beta_2.\ln (H) + \varepsilon$ (linear – Schumacher-Hall, 1933) and Model 6: $V = (DBH^2.H)/\beta_0 + \beta_1.DBH + \varepsilon$ (Takata).

Table 3. Initial characteristics of the soil in the 0.0–0.2 and 0.2–0.4 m layers, 2009.

Attribute	Layers (m)	
	0.0–0.2	0.2–0.4
P (resin), mg dm^{-3}	6	6
Organic matter, g dm^{-3}	12	12
pH (1:2.5 soil/0.01 M $CaCl_2$ suspension)	4.9	4.8
K^+, $cmol_c$ dm^{-3}	0.28	0.18
Ca^{2+}, $cmol_c$ dm^{-3}	1.2	1.0
Mg^{2+}, $cmol_c$ dm^{-3}	0.6	0.6
Al^{3+}, $cmol_c$ dm^{-3}	0.1	0.1
Total acidity pH 7.0 ($H^+ + Al^{3+}$), $cmol_c$ dm^{-3}	2.0	2.1
Base saturation, %†	51	45
Sand, g kg^{-1}	815	783
Silt, g kg^{-1}	104	142
Clay, g kg^{-1}	81	75
Macroporosity, m^3 m^{-3}	0.03	0.03
Microporosity, m^3 m^{-3}	0.34	0.34
Total porosity, m^3 m^{-3}	0.38	0.37
Bulk density, kg dm^{-3}	1.59	1.58
Aggregates > 2.0 mm, %	57.88	52.26
Mean weight diameter, mm	2.76	2.61

† base saturation = 100(Ca^{2+} + Mg^{2+} + K^+/CEC pH 7.0).

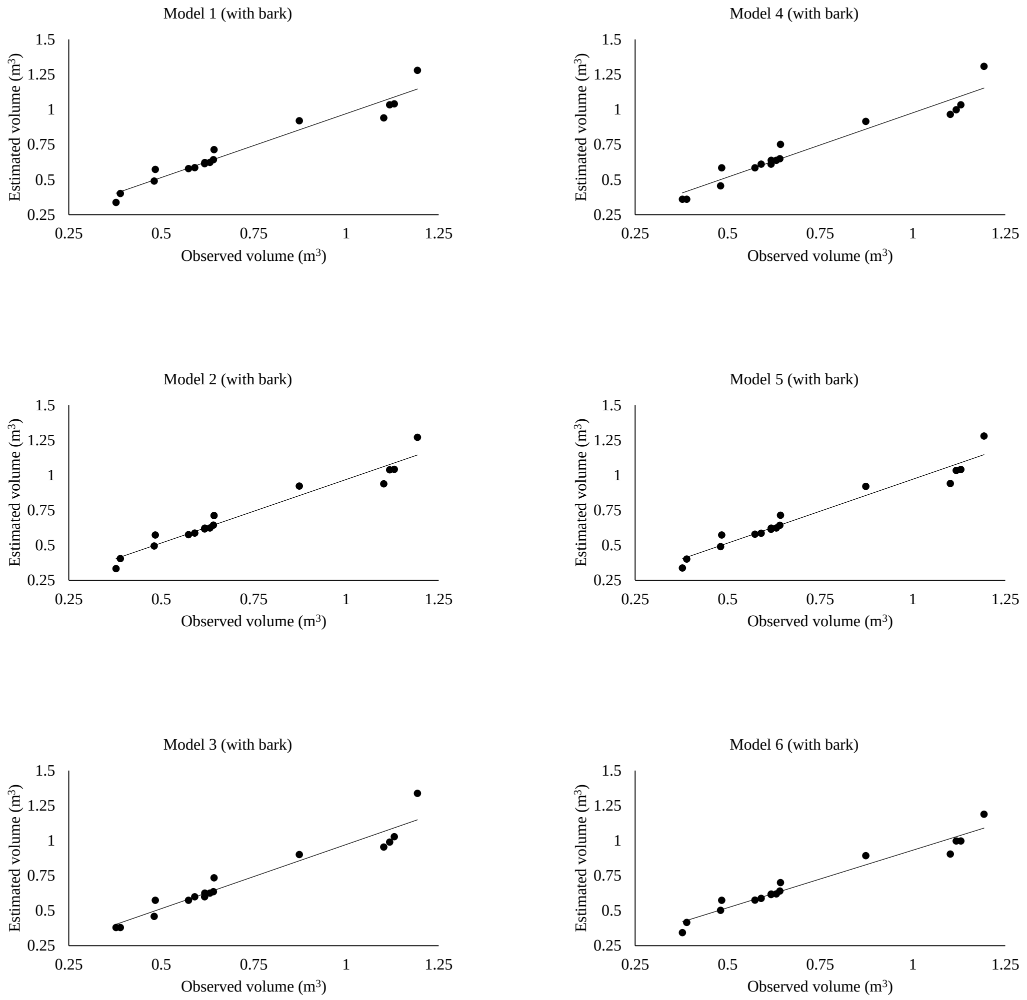

Figure 3. Observed volume × estimated volume of the tested models for eucalyptus hybrid Urograndis H-13, 2016: Model 1: $V = \beta_0.DBH^{\beta_1}.H^{\beta_2} + \varepsilon$ (nonlinear – Schumacher-Hall), Model 2: $\ln(V) = \beta_0 + \beta_1.\ln(DBH^2.H) + \varepsilon$ (Spurr), Model 3: $\ln(V) = \beta_0 + \beta_1.\ln(DBH) + \varepsilon$ (Husch), Model 4: $V = \beta_0 + \beta_1.DBH + \beta_2.DBH^2 + \varepsilon$ (Horenad and Krenn), Model 5: $\ln(V) = \beta_0 + \beta_1.\ln(DBH) + \beta_2.\ln(H) + \varepsilon$ (linear – Schumacher-Hall, 1933) and Model 6: $V = (DBH^2.H)/\beta_0 + \beta_1.DBH + \varepsilon$ (Takata).

Table 4. Crops planted in the September 2009-August 2016 period.

Season	September/March	April/August
2009/10	millet/eucalyptus + soybean	eucalyptus+sunn hemp
2010/11	eucalyptus+maize+palisade grass	eucalyptus+palisade grass
2011/12	eucalyptus+pallisade grass	eucalyptus+palisade grass
2012/13	eucalyptus+pallisade grass	eucalyptus+palisade grass
2013/14	eucalyptus+pallisade grass	eucalyptus+palisade grass
2014/15	eucalyptus+pallisade grass	eucalyptus+palisade grass
2015/16	eucalyptus+pallisade grass	eucalyptus+palisade grass

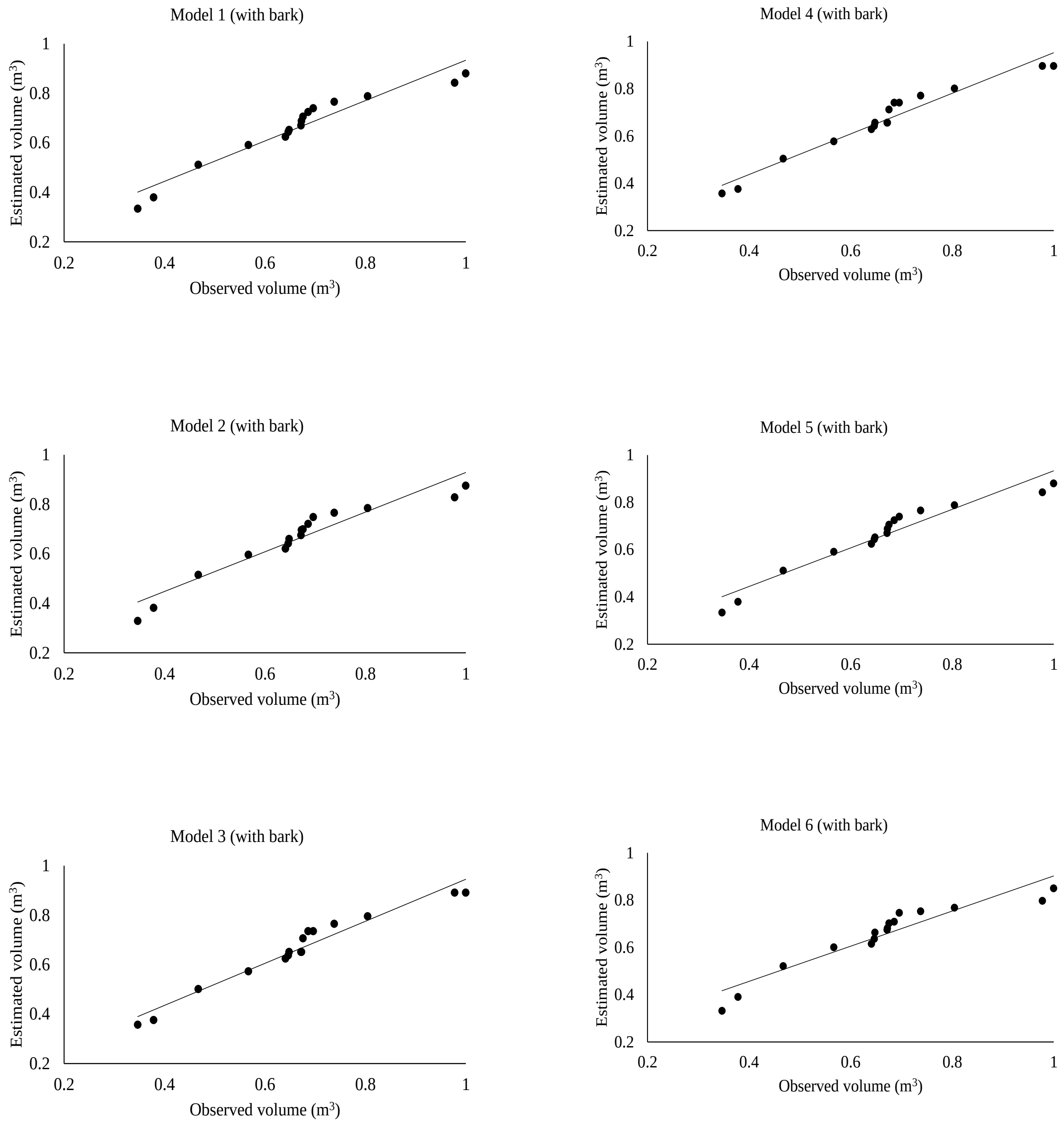

Figure 4. Observed volume × estimated volume of the tested models for eucalyptus hybrid Grancam 1277, 2016: Model 1: $V = \beta_0.DBH^{\beta 1}.H^{\beta 2} + \varepsilon$ (nonlinear – Schumacher-Hall), Model 2: $\ln(V) = \beta_0 + \beta_1.\ln(DBH^2.H) + \varepsilon$ (Spurr), Model 3: $\ln(V) = \beta_0 + \beta_1.\ln(DBH) + \varepsilon$ (Husch), Model 4: $V = \beta_0 + \beta_1.DBH + \beta_2.DBH^2 + \varepsilon$ (Horenad and Krenn), Model 5: $\ln(V) = \beta_0 + \beta_1.\ln(DBH) + \beta_2.\ln(H) + \varepsilon$ (linear – Schumacher-Hall, 1933) and Model 6: $V = (DBH^2.H)/\beta_0 + \beta_1.DBH + \varepsilon$ (Takata).

Table 5. Application of nutrients in the September 2009–August 2016 period.

Season	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
2009/10	15.0	124.0	60.0
2010/11	116.4	91.0	86.4
2011/12	45.0	NA	NA
2012/13	33.0	NA	NA
2013/14	100.0	NA	NA
2014/15	50.0	NA	NA
2015/16	25.0	NA	NA

NA, not applied

millet + eucalyptus, 10/23/2009 eucalyptus + soybean, 11/30/2009

eucalyptus + sunn hemp, 11/01/2010 eucalyptus + maize + palisade grass, 04/27/2011

eucalyptus + palisade grass, 09/23/2011 eucalyptus + palisade grass, 05/23/2016

Figure 5. Intercropping used in the October 2009-May 2016 period.

however, they also concluded that the Stoate model provided the best adjustment among the evaluated volumetric models according to the standard error of estimate. Miguel et al. (2015) observed similar coefficients of determination of the Stoate volumetric model for *E. urophylla*. Mendonça et al. (2015) verified that the Schumacher-Hall model was more accurate than the Spurr model for estimating the volume of *Pinus* species. For *Couratari stellata*, Santos et al. (2018) observed that the Schumacher-Hall model was also the best-performing model, and Oliveira et al. (2017) found that the Schumacher-Hall and Spurr logarithmized models presented the best adjustments. Cruz et al. (2019) evaluated the efficiency of volumetric adjustments for *Lecythis lurida* and observed that, in terms of precision parameters, the Spurr combined variable, Schumacher-Hall and Spurr logarithmized models presented the best values. Oliveira et al. (2018) recommended the Schumacher-Hall model for estimating the merchantable volume of trees of *Khaya ivorensis* at ages close to first thinning (7 years) and final cut (14-15 years).

For an agrosilvipastoral system with 6-year-old eucalyptus planted in three parallel rows (3 x 2 m), Lemos-Junior et al. (2016) verified that the Näslund, Ogaya, Schumacher-Hall, Spurr logarithmic, Honner, Takata and Husch models exhibited adjusted coefficients of determination higher than 87%; the models of Näslund (99.53%) and Ogaya (99.17%) were the best.

Müller et al. (2014) previously reported that the linear Schumacher-Hall model was efficient for estimating the volume of eucalyptus in a silvipastoral system. The strong ability of this model to predict volume is already well recognized in forestry science (Cerqueira et al., 2020), and it is widely used to accurately estimate the volume of wood in forest environments as a function of diameter and full or commercial height (Campos and Leite, 2013).

The estimated average volumes with bark per tree in the present study were similar to those found by Müller et al. (2009) (0.67 m^3 $tree^{-1}$) for a mixed silvipastoral system comprising 10-year-old *E. grandis* (60 plants ha^{-1}) and *Acacia mangium* (45 tree ha^{-1}). The total estimated average volumes with bark per hectare were similar to those reported by Coelho Júnior (2015) (259.93 m^3 ha^{-1}). By contrast, the volumes estimated in this study were higher than those observed by Magalhães et al. (2018) (38 m^3 ha^{-1} on average for 4.7-year-old trees) and Behling et al. (2021) (96 m^3 ha^{-1} on average for 7-year-old trees) in different agrosilvipastoral systems with *E. urophylla* × *E. grandis*.

Since the density of trees is lower in agrosilvipastoral systems than in monoculture tree plantations, the volume of wood per hectare tends to be smaller in the former. Vieira et al. (2013) found a volume of 444.3 m^3 ha^{-1} in a 10-year-old stand of *E. urophylla* × *E. globulus*. Schumacher et al. (2011) reported a volume of 344.4 m^3 ha^{-1} for six-year-old stands of different *Eucalyptus* species. Santana et al. (1999) found volumes ranging from 228 to 473 m^3 ha^{-1} in six-and-a-half-year-old stands of *E. grandis* and *E. saligna* of different genetic materials. In agrosilvipastoral systems, crops such as soybean, maize and palisade grass/beef cattle are cultivated alongside trees, and the economic profitability of these companion crops can compensate for the smaller volume of wood production.

Graphs of residuals are very useful when choosing a model but must be combined with values of adjusted R^2 to verify the mathematical behavior of the model across the regression line (Azevedo et al., 2011). The clear distribution of points on both sides of the zero line, which corresponds to the regression line, indicated homogeneity of variance between the real and estimated data for both hybrids. However, the Takata volumetric model provided a lower range of variation for Urograndis H-13, whereas the nonlinear and linear Schumacher-Hall volumetric models provided a lower range of variation for Grancam 1277.

The distribution of the estimated volume in relation to the observed volume for eucalyptus hybrids Urograndis H-13 and Grancam 1277 exhibited a similar trend for all models tested, with high similarity of the estimated values to the actual values obtained during cubage.

Materials and Methods

Description of site, soil, climate, and treatments

The experiment was carried out at the Advanced Research and Development Center for Rubber and Agroforestry Systems of the Agronomic Institute (IAC) of the São Paulo Agency for Agribusiness Technology (APTA), which is located in the Cerrado biome in the municipality of Votuporanga, São Paulo State, Brazil (20º20'S, 49º58'W and 510 m altitude). The soil in the experimental area is classified as an Arenic Hapludult (Soil Survey Staff, 2014), hereafter referred to as Ultisol, with a sandy texture. The climate in the region is tropical with dry winters (Aw type according to Köppen's classification), with average annual maximum, minimum, and mean temperatures of 31.2°C, 17.4°C and 24°C, respectively, and average annual rainfall of 1328.6 mm. Soil samples were taken at depths of 0.0–0.2 and 0.2–0.4 m for chemical (van Raij et al., 2001), physical (Danielson and Sutherland, 1986), granulometric (Day, 1965), and structural characterizations (Kemper and Chepil, 1965). The results are shown in Table 3.

The experiment followed a randomized block design with four replicates (positions in the experimental area) and two treatments: eucalyptus hybrid Urograndis H-13 (*Eucalyptus urophylla* S. T. Blake × *E. grandis* W. Hill ex Maiden) and eucalyptus hybrid Grancam 1277 (*E. grandis* × *E. camaldulensis* Dehnh.).

Crop management

The agrosilvipastoral system was implemented in an area with degraded pasture that had been cultivated for 10 years. The soil in the area had been managed under conventional tillage with plowing and harrowing. As the soil has a sandy texture, it is susceptible to erosion, and the use of cover crops for soil protection is necessary. Consequently, millet (*Pennisetum glaucum*) was sown between the terraces for soil conservation after tillage in September 2009. In October 2009, the eucalyptus hybrids were planted on the terraces in a simple line system with a spacing of 2 m between trees (plants) and 13.5 m between rows, totaling 370 plants ha^{-1} (density). On November 30, 2009, the millet was desiccated, and soybean was sown between the terraces over the millet straw under no-tillage. The soybean was harvested on April 8, 2010, and sunn hemp (*Crotalaria juncea*) was then sown as a cover crop for soil protection.

The sunn hemp was desiccated on November 29, 2010, and maize was sown between the terraces on the sunn hemp straw on December 15, 2010, under no-tillage. Palisade grass (*Urochloa brizantha* cultivar Marandu) was sown on December 16, 2010; two rows were sown between rows of the maize crop. In September 2011, the area was divided into 1.0-ha plots (paddocks), and four newly weaned beef cattle were introduced per plot for continuous grazing for 24 months until slaughter. After the slaughter of the first group of cattle, a new group of beef cattle was introduced in the area under a rotational grazing system and remained in the area until slaughter. The stocking rate of cattle varied according to the forage supply.

On July 22, 2016, the animals were removed from the area for pasture regeneration, and thinning of the eucalyptus was carried out on July 25–26, 2016.

Table 4 summarizes the crops used in the system, Figure 5 shows the intercropping used, and Table 5 provides the details of the nutrients applied.

Data collection and analysis

On July 26, 2016, a census of 32 plants of each eucalyptus hybrid (eight plants per replicate, four replicates), i.e., a total of 64 plants, was conducted. The circumference at breast height (CBH) of each plant was measured at a height of 1.3 m using a tape measure. The CBH data were then transformed to DBH.

On August 1–3, 2016, the cubage of 16 plants of Urograndis H-13 (four plants per replicate, four replicates) and 16 plants of Grancam 1277 (four plants per replicate, four replicates) was rigorously measured using the Smalian method. First, the commercial height was measured. Next, the plants were divided into 10 sections, and the diameter of each section was measured with a tape measure. The bark thickness of each section was measured to calculate the shelled volume. After obtaining the volumes and heights of the plants, the volumetric models were adjusted to estimate the volumes of the two eucalyptus hybrids.

Volumetric models

Six volumetric models used by Cerqueira et al. (2016) to estimate the total volume with bark of trees were tested:

Model 1: $V = \beta_0.DBH^{\beta 1}.H^{\beta 2} + \varepsilon$ (nonlinear - Schumacher and Hall, 1933);

Model 2: $\ln (V) = \beta_0 + \beta_1.\ln (DBH^2.H) + \varepsilon$ (Spurr, 1952);

Model 3: $\ln (V) = \beta_0 + \beta_1.\ln (DBH) + \varepsilon$ (Husch, 1972);

Model 4: $V = \beta_0 + \beta_1.DBH + \beta_2.DBH^2 + \varepsilon$ (Horenad and Krenn; cited by Cerqueira et al., 2016);

Model 5: $\ln (V) = \beta_0 + \beta_1.\ln (DBH) + \beta_2.\ln (H) + \varepsilon$ (linear - Schumacher and Hall, 1933);

Model 6: $V = (DBH^2.H)/\beta_0 + \beta_1.DBH + \varepsilon$ (Takata; cited by Cerqueira et al., 2016),

where V is volume; DBH is the diameter at breast height; H is the commercial height (m); ln is the Napierian logarithm; β_i are the coefficients determined by regression; and ε is random error. Matlab version 7.10.0 (R2010a) was used to calculate the coefficients.

Criteria for selecting the best model

To select the best model, the following statistical criteria were applied to verify the presence or absence of trends in the dependent variable estimates: a) analysis of variance; b) adjusted coefficient of determination (R^2), and c) graphical analysis of the residuals (Azevedo et al., 2011). The residual (Residual %) of each estimated value is given by Residual (%) = $\frac{(y_i - \hat{y}_i)}{y_i} \times 100$, where Yi is the observed value and $\hat{Y}i$ is the estimated value.

Statistical analysis

Data were submitted to regression analysis and ANOVA (F test) ($P < 0.05$). Microsoft Excel (2016) was used for graphical analysis of the residuals of the tested models.

Conclusion

The present study evaluated six volumetric models for generating estimates of the total volume with bark of eucalyptus hybrids Grancam 1277 and Urograndis H-13 cultivated in an agrosilvipastoral system. The results indicate that (a) the Takata model is most accurate for quantifying the volume of eucalyptus hybrid Urograndis H-13 and (b) the nonlinear and linear Schumacher-Hall models are most accurate for eucalyptus hybrid Grancam 1277.

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