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Morphometric indexes and dendrometric measures for classification of forest sites of *Eucalyptus urophylla* stands

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Abstract

The main goal of this study was to verify the applicability of morphometric indexes and dendrometric measures to assess production capacity and volumetric prognosis of forest sites under *E. urophylla* stands/plantation. During forest measurement inventory, 21 randomized permanent sample plots were monitored from the third to the sixth year of cultivation, registering individuals with standard minimum features, collecting the variables diameter at breast height (DBH), crown diameter (CD), total height (TH), and crown height (CH). A volume estimation equation was adjusted using the software Statistica 7, which were used for estimation the wood volume of each sample in each year of cultivation. Furthermore, other three stand variables were collected: arithmetic mean diameter (MD), quadratic mean diameter (QMD), and dominant height (DH); along with three morphometric indexes: slenderness degree (SD), salience index (SI), and crown formal (CF). Amongst five sigmoidal models adjusted for site classification three of them were considered best choice for different variables: Richards (MD, QMD, and CF); Gompertz (DH); Weibull (SD and SI). All variables presented satisfying adjustment precision for the Clutter prognosis model. Despite a small advantage found in some indexes on statistical tests, there was no significant difference between the six variables on an Analysis of Variance (ANOVA) for volume prediction, which brought us the conclusion that all variables are efficient for site quality classification.

Key words: Brazil; forest management; growth; modeling; production.
Abbreviations: AD%_aggregate difference in percentages; ANOVA_analysis of variance; CD_crown diameter; CF_crown formal; CH_crown height; DBH_diameter at breast height; DH_dominant height; Ei_absolute mean error; MD_arithmetic mean diameter; NapLog_Napierian logarithm; QMD_quadratic mean diameter; SD_slenderness degree; SI_salience index; TH_total height.

Introduction

Nowadays, around 7% of all forest area in the world is composed by planted forests, which corresponds to 264 million hectares. Most of planted forests (nearly 61%) have located in China, India and the United States (Miguel et al., 2016). Meanwhile, in Brazil forest production crops cover over 7.5 million hectares, being responsible for 91% of all industrial wood production in the country. Due to this great contribution, the forest industry has dedicated time and funds in the pursuit of solutions to meet one of the biggest challenges of the 21st century: the growing demand for wood, energy and fibers, without neglecting the maintenance of natural resources and social inclusion (Ibá, 2016). Eucalyptus is the main genus cultivated in the tropics (Epron et al., 2013), due to its fast growth, productivity, great adaptability, diversity of species, and wide use possibility. Two countries have largest planted area of Eucalyptus genus: India with nearly 22% and Brazil with nearly 21% (Miguel et al., 2016). Eucalyptus stands prevail in the Brazilian territory, covering around 5.6 mi hectares. Brazil has a long term history with the genus, which was introduced in the country around 1825 and had its first commercial plantations by the first years of 19th century (Jesus et al., 2015). Therefore, Brazil stands in the lead of global forest production, i.e. an average production of 36 m³/ha.year, and a productivity increase rate of 0.7% per year, considering the past 5 years (Ibá, 2016). In this context, forest management has had a significant contribution leveraging the formation of forest stands in Brazil, aiming at the sustainability of forest companies by making strategic decisions, and observing every condition of demand, productivity, distance and harvesting, and silvicultural treatment costs (Scolforo et al., 2013). An important requirement for the decision-making process in forest stand implementation is forest site classification. Site classification uses site indexes as a quantitative and practical method of evaluating the quality of a given area, since environmental factors are interactively reflected in height and, consequently, volume growth (Campos and Leite, 2017). Due to the fact that site indexes have been frequently used for site classification all around the world, its knowledge is also of great importance in the decision-making process, planning and establishing strategies for the forest sector (Watt et al., 2015).

Among most commonly used methods for site classification, there is the dominant height method described by Assmann (1970), who defines it as the average height of top 100 trees in diameter per hectare. The preference for this principle is given by the relation between dominant height and diameter, which is the variable with greatest influence on wood volume of each individual tree, besides its stability in response to silvicultural treatments. Although widely used, the dominant height method may present errors due to occasional measurement difficulties and the use of hypsometry to estimate height values of several individuals in the stand.

Morphometric indexes are variables that present potential for use in modeling for site classification, and they make it possible to infer stability, vitality and even productivity of forest individuals (Durlo and Denardi, 1998). These indexes, obtained through relations between crown and trunk dimensions are determined to describe growth and production capacity of individuals and stands (Padoin and Finger, 2010). Thus, a key question about this subject may be: Is there any other alternative variable as efficient as Assmann's dominant height, capable to perform site classification in forest stands? In order to answer such a question, this study intends to assess the potential of using morphometric indexes from forest stands, as well as some other dendrometric variables, compared to dominant height. This study also evaluates production capacity of forest sites and to perform production prognosis in an *E. urophylla* S.T. Blake stand, located at the state of Goiás, Brazil.

Results and Discussion

Adjustment and selection of best site classification model

Tables 1 to 6 present the results of the adjustments of the site capacity classification models, considering the dendrometric measures – arithmetic mean diameter (MD), quadratic mean diameter (QMD), and dominant height (DH) – and the morphometric indexes – slenderness degree (SD), salience index (SI), and crown formal (CF) – from the *Eucalyptus urophylla* stand. In general, all models presented satisfying adjustment for all analyzed measures and indexes, once they have a typical behavior that properly represents the growth of organisms. Therefore, the selection of the best model not only considered the criteria proposed by Draper and Smith (1998), but also considered the recurring use in other studies and the ease of use.

The most precise model to estimate site quality for MD (Table 1), QMD (Table 2) and CF (Table 6) was the Richard's model, while the Gompertz' model was the most adequate one using DH (Table 3). Finally, the best estimates for site quality based on SD and SI were obtained using Weibull's model (Tables 4 and 5, respectively). Therefore, these were the chosen models for each case.

There are many published studies that prove the suitability and efficiency of sigmoidal models for site quality classification in forest plantations (Machado et al., 2010; Zlatanov et al., 2012; Retslaff et al., 2015).

Fig 1 presents the anamorphic site curves obtained from each selected model by applying the guide curve method. It is important to observe that, besides the good adjustment of the sigmoidal models all data is located within a productive class, with minimal exceptions.

Adjustment results of Clutter's model

Table 7 presents results for the adjustment of the Clutter model for volumetric production prognosis in the stand based on each dendrometric measurement and each morphometric index of evaluation of site quality. The adjustment of the Clutter model presented a satisfying precision for every analyzed situation of site classification, presenting low, acceptable values of standard error of estimate and high values of coefficient of determination. Thus, all results obtained so far prove that every situation tested (dendrometric measures and morphometric indexes) to evaluate production capacity of forest sites, as well as for the future production prognosis are valid for the stand analyzed in this study.

Some other studies have already put to test the precision of statistic models to estimate production capacity of forest sites, besides testing it for the prognosis of forest production, using other dendrometric measures besides DH. As an example of that, Leite et al. (2011) tested the efficiency of dominant diameter as an alternative variable to DH to classify the quality of forest sites. The authors have concluded that such variable presented similar results to those obtained using the DH. Sabatia and Burkhart (2014) used biophysical variables (climatic and edaphic) to estimate site indexes of *Pinus taeda* plantations in the United States and obtained satisfactory results.

Although all tested variables in this study have presented similar estimates, the index of crown formal (CF) and the quadratic mean diameter (QMD) stood out because they presented slightly higher results.

Validation of adjusted selected models

Using a correlation analysis between volumetric production in each sample year and the studied variables (dendrometric measures and morphometric indexes), we observed that the volumetric production of the stand has presented significant correlation only with few measures and indexes through the four sample years (Table 8) in the first stage of validation of the Clutter model adjustment.

Dominant height did not present significant correlation with volume in any sample year. This fact might be explained with a probable stabilization of trees' height of stand in the studied period.

Results showed that volumetric production has high and negative correlation with slenderness degree and salience index, which explains the descent behavior of the site curves generated with these two indexes (Fign/ nnj 1). The same behavior was observed in a Eucalyptus plantations study in Santa Maria, Rio Grande do Sul, Brazil (Wink et al., 2012).

When it comes to the validation criteria of aggregate difference in percentages (AD%) and absolute mean error (Ei), all tested measures and indexes presented a similar behavior (Table 9). Both validation measures presented positive values for every tested variables, demonstrating the tendency of the Clutter model to underestimate the volumetric production of the stand. Although such underestimations were small but they did not compromise the quality of the adjustment. Sabatia and Burkhart (2014) found the same underestimation tendency on their model for site index prediction.

The arithmetic mean diameter and the salience index were the most efficient measures for production prognosis, considering these two validation criteria (Table 9). According to Miguel et al. (2015), variables which present Ei values close to zero demonstrate a better capacity to perform the desired estimate accurately. Such behavior occurs with the proposed variables, indicating their good suitability for the prognosis of volumetric production.

Application of variance analysis (ANOVA) as validation criteria for the adjusted model in each analyzed situation (Table 10) allowed us to observe the lack of significant difference between the production prognosis obtained with each measure and each index. The results also show that there is no significant effect of interaction, which means that a measure or index does not influence forest site quality. The fact that no significant difference was found between measures and indexes allows us to conclude that all these variables are capable of explaining and predicting the

Table 1. The parameters and precision statistics of four best statistical models adjusted to evaluate productive capacity of forest sites based on arithmetic mean diameter (MD) in a *Eucalyptus urophylla* S.T. Blake plantation, Goiás, Brazil.

Models	Estimated model's parameters				Precision Statistics		
	β_0	β_1	β_2	β_3	Syx (cm)	Syx%	R^2 adjusted
Logistic	15.193	5.145	-0.690		0.63	5.32	0.89
MMF	8.906	121784.782	14.148	8.299	0.61	5.16	0.90
Richards	13.967	17.909	-3.514	17.991	0.61	5.16	0.90
Weibull	13.969	5.663	-0.000986	4.772	0.61	5.16	0.90

Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination; β_0, β_1, β_2 e β_3 = model's parameter.

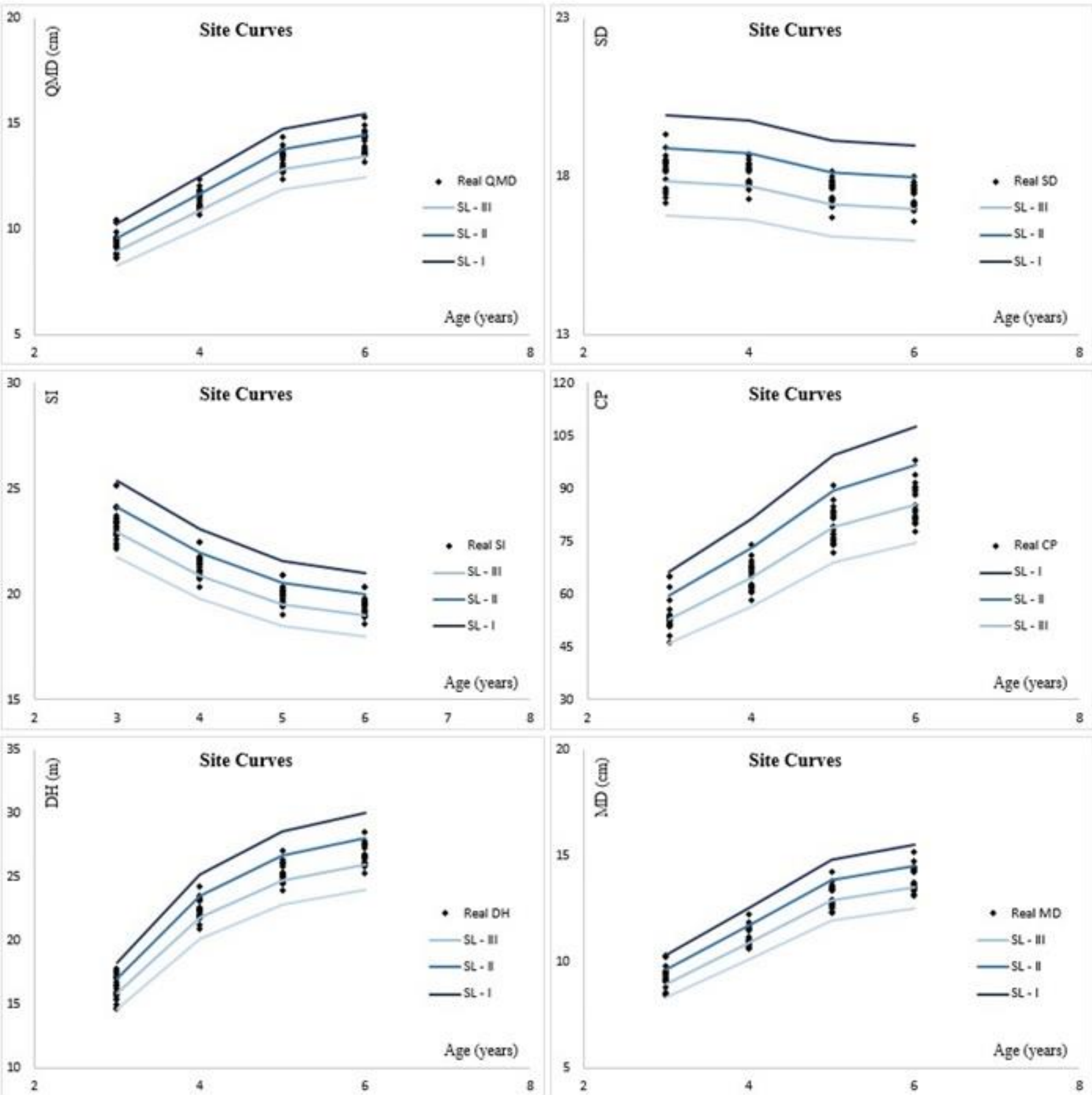

Fig 1. Site index curves generated based on dendrometric measures (MD, QMD, and DH) and morphometric indexes (SD, SI, and CF), for a *Eucalyptus urophylla* S.T. Blake, Goiás, Brazil. SL – III = superior limit of site III; SL – II = superior limit of site II; SL – I = superior limit of site I.

Table 2. The parameters and precision statistics of four best statistical models adjusted to evaluate productive capacity of forest sites based on quadratic mean diameter (QMD) in a *Eucalyptus urophylla* S.T. Blake plantation, Goiás, Brazil.

Models	Estimated model's parameters				Precision Statistics		
	β_0	β_1	β_2	β_3	Syx (cm)	Syx%	R^2 adjusted
Logistic	15.376	5.205	-0.692		0.61	5.08	0.90
MMF	8.969	94152.235	14.343	8.123	0.59	4.93	0.91
Richards	14.151	16.813	-3.307	16.702	0.59	4.93	0.91
Weibull	14.151	5.815	-0.001144	4.676	0.59	4.93	0.91

Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination; β_0, β_1, β_2 e β_3 = model's parameter.

Table 3. Model's parameters and precision statistics of four best statistical models adjusted in order to evaluate productive capacity of forest sites based on dominant height (DH) in a *Eucalyptus urophylla* S.T. Blake plantation, Goiás, Brazil.

Models	Estimated model's parameters				Precision Statistics		
	β_0	β_1	β_2	β_3	Syx (cm)	Syx%	R^2 adjusted
Gompertz	27.436	-2.165	-0.935		0.83	3.68%	0.96
Logistic	27.152	19.825	-1.126		0.83	3.69%	0.96
MMF	-21.135	7.809	28.874	2.852	0.83	3.70%	0.96
Weibull	28.439	-599.052	-2.064	0.576	0.83	3.70%	0.96

Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination; β_0, β_1, β_2 e β_3 = model's parameter.

Table 4. Model's parameters and precision statistics of four best statistical models adjusted in order to evaluate productive capacity of forest sites based on slenderness degree (SD) in a *Eucalyptus urophylla* S.T. Blake plantation, Goiás, Brazil.

Models	Estimated model's parameters				Precision Statistics		
	β_0	β_1	β_2	β_3	Syx (cm)	Syx%	R^2 adjusted
Logistic	0.960	-0.950	-0.00101		0.41	2.31%	0.93
MMF	17.305	0.0000000643	18.241	-10.988	0.40	2.27%	0.96
Richards	18.214	-78.255	-22.965	1140.665	0.41	2.32%	0.93
Weibull	18.214	-0.889	-858361.041	-9.433	0.40	2.26%	0.96

Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination; β_0, β_1, β_2 e β_3 = model's parameter.

Table 5. Model's parameters and precision statistics of four best statistical models adjusted in order to evaluate productive capacity of forest sites based on salience index (SI) in a *Eucalyptus urophylla* S.T. Blake plantation, Goiás, Brazil.

Models	Estimated model's parameters				Precision Statistics		
	β_0	β_1	β_2	β_3	Syx (cm)	Syx%	R^2 adjusted
Logistic	18.200	-0.850	-0.448		0.53	2.56%	0.89
MMF	19.060	0.000355	24.479	-5.992	0.53	2.55%	0.89
Richards	34.541	7.662	-2.363	36.504	0.64	3.08%	0.85
Weibull	23.595	-4.597	-872.787	-5.156	0.53	2.55%	0.89

Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination; β_0, β_1, β_2 e β_3 = model's parameter.

Table 6. Model's parameters and precision statistics of four best statistical models adjusted in order to evaluate productive capacity of forest sites based on crown formal (CF) in a *Eucalyptus urophylla* S.T. Blake plantation, Goiás, Brazil.

Models	Estimated model's parameters				Precision Statistics		
	β_0	β_1	β_2	β_3	Syx (cm)	Syx%	R^2 adjusted
Logistic	100.665	5.124	-0.574		4.71	6.65%	0.88
MMF	50.261	35076.793	89.091	7.196	4.61	5.51%	0.89
Richards	85.980	37.779	-6.845	33.640	4.61	5.51%	0.89
Weibull	86.638	-39.104	-0.000842	4.729	4.61	6.51%	0.89

Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination; β_0, β_1, β_2 e β_3 = model's parameter.

Table 7. Clutter model adjusted for wood volume prognosis ($m^3.ha^{-1}$), in function of dendrometric measures (MD, QMD, DH) or morphometric indexes (SD, SI, CF), for an *Eucalyptus urophylla* S.T. Blake stand, Goiás, Brazil.

Variable	Clutter Model Adjusted	Syx	Syx%	R^2 adjusted
MD (cm)	$NLV_2 = 4.738 - 7.234.S^{-1} - 3.682.I_2^{-1} + 0.606.\left(\frac{I_1}{I_2}\right).NL(G_1) + 1.299.\left(1-\frac{I_1}{I_2}\right) + 0.0851.\left[\left(1-\frac{I_1}{I_2}\right).S\right] + \varepsilon$	7.96	3.81	0.97
QMD (cm)	$NLV_2 = 3.590 - 3.689.S^{-1} - 2.562.I_2^{-1} + 0.826.\left(\frac{I_1}{I_2}\right).NL(G_1) + 2.246.\left(1-\frac{I_1}{I_2}\right) + 0.0759.\left[\left(1-\frac{I_1}{I_2}\right).S\right] + \varepsilon$	8.85	4.24	0.96
DH (m)	$NLV_2 = 3.158 + 1.465.S^{-1} - 2.426.I_2^{-1} + 0.853.\left(\frac{I_1}{I_2}\right).NL(G_1) + 3.867.\left(1-\frac{I_1}{I_2}\right) - 0.186.\left[\left(1-\frac{I_1}{I_2}\right).S\right] + \varepsilon$	9.43	4.52	0.95
SD	$NLV_2 = 3.009 + 7.446.S^{-1} - 2.709.I_2^{-1} + 0.797.\left(\frac{I_1}{I_2}\right).NL(G_1) + 5.494.\left(1-\frac{I_1}{I_2}\right) - 0.133.\left[\left(1-\frac{I_1}{I_2}\right).S\right] + \varepsilon$	8.85	4.24	0.96
SI	$NLV_2 = 3.150 + 12.697.S^{-1} - 3.175.I_2^{-1} + 0.706.\left(\frac{I_1}{I_2}\right).NL(G_1) + 3.769.\left(1-\frac{I_1}{I_2}\right) - 0.048.\left[\left(1-\frac{I_1}{I_2}\right).S\right] + \varepsilon$	8.92	4.27	0.96
CF	$NLV_2 = 4.521 - 23.588.S^{-1} - 3.743.I_2^{-1} + 0.596.\left(\frac{I_1}{I_2}\right).NL(G_1) + 1.534.\left(1-\frac{I_1}{I_2}\right) + 0.0104.\left[\left(1-\frac{I_1}{I_2}\right).S\right] + \varepsilon$	7.94	3.80	0.97

V_2 = estimated future volume (m3.ha-1); S = site index; NL = Napierian logarithm; I_1 = present age (years); I_2 = future age (years); G_1 = present basal area (m2.ha-1); ε = associated error. Syx = absolute estimate standard error; Syx% = relative estimate standard error; R^2 = coefficient of determination.

Table 8. Pearson's correlation test results for correlation between wood volume ($m^3.ha^{-1}$) per age and tested variables (dendrometric measures and morphometric indexes) in an *Eucalyptus urophylla* S.T. Blake, Goiás, Brazil.

Variables	Volume ($m^3.ha^{-1}$)			
	3 years	4 years	5 years	6 years
MD (cm)	0.63 *	0.54 *	0.27	0.61 *
QMD (cm)	0.56 *	0.39	0.18	0.47 *
DH (m)	0.47 *	-0.32	-0.31	-0.31
SD	-0.51 *	-0.62 *	-0.69 *	-0.69 *
SI	-0.78 *	-0.72 *	-0.75 *	-0.75 *
CF	0.32	0.40	0.51 *	0.52 *

*Significant correlation value for a 0.05 level of significance; MD = arithmetic mean diameter; QMD = quadratic mean diameter; DH = dominant height; SD = slenderness degree; SI = salience index; CF = crown formal.

Table 9. Aggregate difference in percentages (AD%) and absolute mean error (Ei) values obtained through validation of the Clutter model adjustment for volumetric production prognosis in function of different variables of an *Eucalyptus urophylla* S.T. Blake stand, Goiás, Brazil.

Variables	AD%	Ei (m^3/ha)
MD (cm)	0.43%	0.7184
QMD (cm)	1.76%	2.9527
DH (m)	1.72%	2.8885
SD	1.67%	2.8068
SI	0.23%	0.3857
CF	1.46%	2.4541

MD = arithmetic mean diameter; QMD = quadratic mean diameter; DH = dominant height; SD = slenderness degree; SI = salience index; CF = crown formal.

Table 10. Factorial ANOVA results for validation of Clutter model adjustment for volumetric production prognosis in function of different variables of an *Eucalyptus urophylla* S.T. Blake stand, Goiás, Brazil.

Variation Source	SS	Df	Ms	Significance
Factor A (Indexes)	248.23	5	49.65	Ns
Factor B (Sites)	13168.83	2	6584.41	Ns
Interaction	1444.18	10	144.41	Ns
Treatments	14861.24	20	743.06	Ns
Errors	669059.36	147	4551.42	
Total	683920.59	167	4095.33	

SS = Sum of squares; Df = degrees of freedom; Ms = mean square; Ns = Not significant.

Table 11. Statistical models adjusted to express productive capacity of forest sites, based on dendrometric measures (MD, QMD, DH) and morphometric indexes (SD, SI, CF).

Model	Equation
Gompertz	$Y = \beta_0 . e^{-e^{(\beta_1 - \beta_2 . I)}} + \varepsilon$
Logístico	$Y = \beta_0 / (1 + \beta_1 . e^{-\beta_2 . I}) + \varepsilon$
MMF	$Y = (\beta_0 . \beta_1 + \beta_2 . I^{\beta_3}) / (\beta_1 + I^{\beta_3}) + \varepsilon$
Richards	$Y = \beta_0 / (1 + e^{\beta_1 - \beta_2 . I})^{\frac{1}{\beta_3}} + \varepsilon$
Weibull	$Y = \beta_0 - \beta_1 . e^{(-\beta_2 . I^{\beta_3})} + \varepsilon$

Y = estimated variable (MD, QMD, DH, SD, SI e CF); MD = mean diameter (cm); QMD = quadratic mean diameter (cm); DH = dominant height (m); SD = slenderness degree; SI = salience index; CF= crown formal; I = stand's age (years); β_0, β_1, β_2 e β_3 = model's parameters; ε = associated error.

volumetric production, since the real volume values was also included in ANOVA as a control treatment, which corroborates with those demonstrated by the validation tests. Furthermore, the lack of significant difference between DH and the other dendrometric measures and morphometric indexes, considered as an alternative for site classification in this study, answering the specific objective proposed in this research, finding an alternative variable to DH for the classification of forest site productive quality.

Materials and Methods

Plant materials and description of the study area

This study was performed in a stand of *Eucalyptus urophylla* S.T. Blake, a highly productive clone, implanted in 2009, within a 320 ha area, with spacing of 3 × 2m, resulting a density of 1,667 trees per hectare. The stand is located in Niquelândia, State of Goiás, Brazil, within coordinates 14º24' 8.4"S and 48º 44' 31"W. The climate is classified as Aw, according to the climatic classification of Köppen (Alvares et al., 2013), which means a characteristic tropical climate, with dry winter. Annual mean precipitation is 1.713 mm, while annual mean temperature of 24.6º C, with maximum of 25.9º C (during September) and minimum of 22.9º C (during June). The region is located at 592 m of altitude, while soil is mostly a dystrophic red-yellow latosol, deep and drained (Embrapa, 2013).

Data gathering

Starting at 2012, a continuous forest inventory was performed. Twenty-one permanent sample plots were established with 500 square meter of dimension each one (20 x 25 m), randomly distributed within stand's total area. In each sample, all trees with at least 5 cm of diameter at breast height (DBH) were registered, and the following variables: DBH, crown diameter (CD), total height (TH), and crown height (CH) were collected. Afterwards, the same variables were collected annually between 2013 and 2015.

Dendrometric measures calculation

From the annual data collected (2012 – 2015) in each sample plot, the dendrometric measures of arithmetic mean diameter (MD), quadratic mean diameter (QMD), and dominant height (DH), as well as the morphometric indexes slenderness degree (SD), salience index (SI), and crown formal (CF) were determined according to the following relations:

$$MD_i = \sum DBH_{ij} / n_i \quad (1)$$

$$QMD_i = \sqrt{4 \cdot \bar{g}_i / \pi} \quad (2)$$

$$DH_i = \sum TH_{ij} / n_{ij} \quad (3)$$

$$SD_i = TH_j / DBH_j \quad (4)$$

$$SI_i = CD_j / DBH_j \quad (5)$$

$$CF_i = CD_j / CH_j \quad (6)$$

where MD_i = arithmetic mean diameter of sample plot i (cm); DBH_{ij} = diameter at breast height of tree j at sample plot i (cm); n_i = number of trees at sample plot i; QMD_i = quadratic mean diameter of sample plot i (cm); $\bar{g}_i$ = mean sectional area of sample plot i (m^2); π = value of pi; DH_i = mean height of 100 trees with biggest DBH in one hectare at sample plot i (m); TH_{ij} = total height of each one of the trees with biggest DBH j at sample plot i (m); n_{ij} = number of trees with biggest DBH j at sample plot i; SD_i = slenderness degree of sample plot i; TH_j = total height of tree j (m); DBH_j = diameter at breast height of tree j (cm); SI_i = salience index for sample plot i; CD_j = crown diameter of tree j (cm); CF_i = crown formal of sample plot i; CH_j = crown height of tree j (m).

Models and adjustment procedures

The total volume for each tree at the sample plot was also estimated by using the volumetric model proposed by Schumacher and Hall (1993) (7), which is the most widely used model to estimate individual tree volume for different species (Azevedo et al., 2011; Sales et al., 2015):

$$V = \beta_0 . DBH^{\beta_1} . TH^{\beta_2} + \varepsilon \quad (7)$$

Where, V = estimated volume per tree (m^3); DBH = diameter at breast height (cm); TH = total height (m); β_0, β_1, β_2 = model's parameters; ε = associated error.

Schumacher-Hall's volumetric model was adjusted for each sample year using the Software Statistica 7 (Statsoft, 2007), while 37, 93, 92, and 62 individuals were submitted to Smalian's method to estimate tree stem and log volume by section at age of 3, 4, 5, and 6 years old, respectively. The trees submitted to Smalian's were selected according to the absolute frequency of each diameter class within the stand, proportionally. Afterwards, the total volume per hectare for each sample plot was estimated for the sample years (2012 – 2015). In order to assess production capacity of the stand, the three dendrometric measures (MD, QMD, DH), and also previously mentioned three morphometric indexes (SD, SI, CF) were tested, adjusting five sigmoidal models for each one of these (Table 11). The guide curve method was used for such adjustments, considering a reference age of 6 years old and three productivity classes, since this method is widely used in Brazil. Model adjustment was performed using the software CurveExpert Basic 1.4 (Hyams, 2010) with data from 17 sample plots, randomly chosen. The remaining plots were used to validate selected models. The best model was chosen according to the following precision measures: graphical analysis of waste, residual standard error, and coefficient of determination (Draper and Smith, 1998). Forest production prognosis was performed by adjusting Clutter`s model (8), in its original form (Clutter, 1963), using Microsoft Excel 2013:

$$NapLog(V_2) = \beta_0 + \beta_1 S^{-1} + \beta_2 I_2^{-1} + \beta_3 \left(\frac{I_1}{I_2}\right) NapLog(G_1) + \beta_4 \left(1 - \frac{I_1}{I_2}\right) + \beta_5 \left[\left(1 - \frac{I_1}{I_2}\right) . S\right] + \varepsilon \quad (8)$$

Where V_2 = estimated future volume (m^3.ha-1); β_0, β_1, β_2, β_3, β_4 e β_5 = model's parameters; S = site index, classified for each dendrometric measurement and each morphometric index; NapLog = Napierian logarithm; I_1 = present age (years); I_2 = future age (years); G_1 = present basal area (m^2.ha-1); ε = associated error. For Clutter model adjustment, all 21 permanent sample plots were classified at sixth year in three classes of real volumetric production: high, medium, and low. A total number of 15 plots were selected for the adjustment, while the six remaining plots were used to validate the prognosis.

Statistical analysis for validate adjusted models

The validation process for all used models, including sigmoidal and prognosis, considered three evaluation criteria: (i) Pearson's correlation test to verify the existence of significant correlation between the studied variables (dendrometric measures and morphometric indexes) and volumetric production registered through the sample years; (ii) the calculation of aggregate percentage difference and absolute mean error; (iii) factorial ANOVA (analysis of variance), to verify the existence of significant difference between real volume values and projected volume values obtained by using the studied variables in prognosis model.

Conclusion

This study presented satisfactory precision statistics for the different adjusted models for site classification, considering three dendrometric measures (MD, QMD, and DH) and three morphometric indexes (SD, SI, and CF), as well as for the Clutter model, adjusted in function of each of these variables, intended to prognosticate the volumetric production of the stand. Although the variables quadratic mean diameter (QMD), crown formal (CF) and salience index (SI) have slightly stood out in precision, all dendrometric measures and morphometric indexes tested in this study may be used for site classification in the stand, as well as to prognosticate the volumetric production, since all of them have estimated volumetric productions that were statistically equal to real values.

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