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Stand Volume Modeling Of *Mimosa Scabrella* In Native Bracatinga Forests

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ABSTRACT

Bracatinga (*Mimosa scabrella* Bentham) is a pioneer native species of the Leguminosae family. The forest formations known as *bracatinga* forest or "*bracatingais*" are composed initially only by the *Mimosa scabrella* wich over the years, is being replaced by several hardwood species. They are common forest formations in the small properties of the metropolitan region of Curitiba, being an important source of income for the small owners of this region. The wood produced in these *bracatinga* forests is mainly sold for firewood and charcoal**.** In order to facilitate the quantification of volumetric wood production, the objective of this research work was to model the volume of firewood with bark per unit of area for *bracatinga*. The data base came from 320 plots measured in stands with ages varying from 3 to 20 years, measured between 1996 and 2011 in several counties of the metropolitan region of Curitiba. In these plots were measured total height and diameter at breast height (DBH) of all the trees, with DBH ≥ 5 cm. The individual volume of each tree in every plot was calculated using equations fitted for these *bracatinga* forests. They were fitted 29 forest models selected from the forest literature, plus one arithmetic and one logarithmic by the forward stepwise process**.** The logarithmic equation fitted by the forward stepwise process was the one with the best overall performance, with $R^2 = 0.993$ and Syx% = 3.46. Among the 29 models taken from the literature, the non-linear equation corresponding to the model of Takata (1959) was the one that presented the best result. The use of the variable selection process by means of the forward stepwise methodology resulted in equations with higher levels of precision and fit than the equations fitted using models from the literature, being that the logarithmic equation fitted by the "forward stepwise" process was validated and considered suitable for use in the inventories of *bracatinga*.

INTRODUCTION

Mimosa scabrella (Bracatinga) is an important species, especially for the small landowners who have been empirically managed it for more than 100 years. It is a pioneer species that forms almost pure stands at the beginning, and that every 7 years it is done clear cutting of the stand for use as firewood and charcoal. In view of the empiricism of the management used by the producers arises the need to develop techniques and methodologies that subsidize the application of a more consistent and rational management. This is what we seek, at least in part, to achieve with this research.

These *bracatinga* forests, as observed by Silva *et al*. (2016), have as characteristic to be formed almost exclusively by the species *Mimosa scabrella* in the initial phase. Several other secondary species substitute the *bracatinga* over the years; after 11 years of age the stand has the characteristic of a secondary forest, already with predominance of several others species.

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In the metropolitan region of Curitiba, the *bracatinga* forests are managed for the production of wood that is used mainly as fire wood and charcoal, besides other uses. These *bracatinga* forests, have great social and economic importance for the region because it is considered as “a green saving” by the small farmers who manage it. Carpanezzi and Laurent (1988), cited by Mazuchowski (2014) identify two management systems of *bracatinga* stands in the metropolitan region of Curitiba, being a traditional system and the other agroforestry.

Mazuchowski and Angelo (2012) state that the productive process of *bracatinga* maintains a relative equality between the annual cutting area and the regeneration area of *bracatinga* forests, forming a regional mosaic landscape of *bracatinga* forests with sequential ages of tree growth, similar to a chessboard, with average annual cut of *bracatinga* observed in the properties, is less than 20 hectares, with a predominance of compartments between 2 and 5 hectares of production and cutting.

As forests are dynamic biological systems that continually change, it becomes necessary to quantify this change for management decision making. In this respect, mathematical modeling has played a key role in forest management.

Usually the volumetric stock of wood in a forest stand is obtained by the sum of the estimated volumes by means of equations for individual trees and expressed per unit of area (hectare).

According to Scolforo (2005), the construction of stand equations (modeling per unit of area) is an alternative to the use of models for individual trees and has as purpose the reduction of work and costs of the forest inventory, mainly in the measurement of individual tree heights, which is a laborious and subject to errors. Figueiredo Filho *et al*. (1982) state that the application of mathematical models to estimate stand volume is only justified when the independent variables are easy to measure in the field and thus bring reduction of labor and cost without significant losses of accuracy.

The volume equations of the forest stand are functionally similar to the volume equations for individual trees, however, they use independent variables referring to the unit of area, such as, basal area, mean tree height, mean dominant height, mean DBH, quadratic diameter and number of trees (Scolforo, 2005). These independent variables are obtained from a fixed area plot or sampling point (Bitterlich for example), then extrapolated to the hectare and correlated with the stand volume (volume per hectare).

Among the studies on volume modeling per unit of area Rosot *et al*. (1990) pointed out several international authors who started and developed the modeling per unit of area, such as , Konig (1846); Weise (1881); Schifel (1881); Spurr (1951); Gevorkiantz and Olsen (1955); Buckman (1961); Vuolkila (1965); Brinkman (1967); Schlaegel (1971); Farot (1977); and Cole (1971).

The Brazilian forest literature pointed out several researches, such as: Figueiredo Filho *et al*. (1982), Silva, (1985); Rosot *et al*. (1990), Machado and Pizatto (1998), Oliveira *et al*. (2005), and Machado *et al*. (2008a). Recently, Cysneiros *et al*. (2016) modeled the commercial volumetric stock in an Ombrophilous forest in the southwest of the Amazon.

Other recent work deals with the modeling per unit of area for other stand variables, such as Ribeiro *et al*. (2012),which modeled macronutrients for bracatinga, Souza *et al*. (2013) and Souza *et al*. (2014) that modeled, respectively, organic carbon, total biomass and firewood for native bracatinga forests in the metropolitan region of Curitiba .

Machado *et al*. (2008a), modeled the stand volume for *Mimosa scabrella* (*bracatinga*) in the metropolitan region of Curitiba. On that occasion, using a database of 229 plots distributed between ages from 3 to 18 years, they fitted 29 mathematical models selected from the forest literature to estimate volume per unit of area. This was the only one work of stand modeling for *bracatinga*.

In general, this work will contribute to the improvement in the quantification process of the wood volume in the native bracatinga stands of the metropolitan region of Curitiba, Paraná, Brazil. The use of the best adjusted equation generates time and cost savings for the owners of the “bracatingais”, allowing to obtain the volume per unit area directly by the equation developed in this work, using basic measurements in the forest inventory process, such as DBH's, average height and dominant height.

With the increase of the data base including other ages, the individual volume modeling and the fitted of the site equation for the stands, it became necessary to re-model the volume of *Mimosa scabrella* firewood in the *bracatinga* forests. In this way, the objective of this work was to model the volume of firewood per unit of area (stand volume) of *bracatinga* of the metropolitan region of Curitiba.

MATERIAL AND METHODS

Characterization of the study area:

For the development of this research were used data from native *bracatinga* forests of the metropolitan region of Curitiba, collected in fourteen municipalities.

The study area is located in the First Paraná Plateau, which according to the Köppen classification system presents a climate of the type Cfb, which corresponds to the temperate, humid mesothermic climate with no hidric deficit, with four well defined seasons, with hot summers and rainy, and cold winters with occasional dry periods. The average annual temperature is around 17ºC, with minimums of 11ºC and maximum of 24ºC. The average annual precipitation is between 1,400 and 1,600 mm, with slight decrease in winter, with no water deficits occurring (Caviglione *et al*., 2000).

The geographical coordinates of the study area are limited to the north by latitude 24°58'11" S, south latitude 25°55'44" S, west by longitude 49°29'09" W and east by longitude 49º03’58" W (Silva *et al*., 2016).

According to Souza, *et al*. (2013), the eastern, northern and southern regions of the studied area has strong influence of the Serra do Mar, mean while the western part, it has influence of the Devonian Escarpment. In the northern region, where the relief is more rugged, altitude ranges from 850 m in Agudos do Sul to 980 m in Bocaiúva do Sul.

In this region, the predominant soils are: Hapless Cambisol Aluminum and dystrophic, Dystrophic Red Argisol and Yellow Red Latosol Alic, Neosols, besides some areas of Aluminum and Dystrophic Humic Cambisols associated with Rock Outcrops (Bhering *et al*., 2008).

Data base:

The data for modeling the volume of *bracatinga* stands came from 320 temporary plots, randomly distributed in *bracatinga* forests with ages varying from 3 to 20 years; it was not found *bracatinga* forests at the age of 16 years. From each plot all diameters were measured at 1.30 m from the ground level (DBH) and the total height of the *bracatinga* and other hardwood species. Out of the 320 plots, in 20 of them the *bracatinga* was not present and in 81 of them only the *bracatinga* was present, remaining 219 plots with mixed species composition (*bracatinga* + hardwoods).

The ages of *bracatinga* in the plots were determined by local information (owners), checked when necessary, by reading the growth rings (Silva *et al.*, 2016).

In this sample there are plots of different sizes, and the values of the variables originating from each plot were extrapolated to hectare, as a way to standardize them. The number of sample units by age, for *bracatinga* and the other hardwoods are presented in Table 01.

The data of each plot were organized to meet the proposed objective and to develop the modeling process by the following procedures: Calculation of the mean heights ($\bar{h}$), mean diameters ($\bar{d}$)and mean square diameter (dg) of the trees in the plots; Determination of dominant heights (h_{dom}) of each plot with subsequent site classification; Calculation of the individual of firewood volume of each tree with extrapolation to hectare; Calculation of the cross-sectional areas of each tree and its extrapolation to hectare.

Table 01: Sample intensity, by age, in the *bracatinga* forests of the metropolitan region of Curitiba, Paraná.

Age (years)	Number of Total Plots	Number of Plots With *Bracatinga*	Number of Plots With Hardwoods	Sample Area (m^2)	Plots Area (m^2)
3	8	8	0	800	100
4	21	21	5	4920	234
5	27	27	6	6315	234
6	32	32	18	8125	254
7	36	36	24	9610	267
8	22	22	17	5800	264
9	25	25	22	6720	269
10	16	16	16	4800	300
11	18	18	18	5720	318
12	15	15	15	4270	285
13	19	19	18	6000	316
14	21	21	21	6900	329
15	13	13	12	5000	385
17	6	6	6	3400	567
18	9	9	9	2980	331
19	29	11	29	5800	200
20	3	1	3	900	300
Total	320	300	239	88060	

Site classification for bracatinga:

Initially the observed values of dominant height - h_{dom} in each plot were determined considering the concept of ASSMANN for dominant height, that is, the mean heights of the 100 thickest trees per hectare. Every one of the n plots was classified into site classes based on the site curves for *bracatinga* constructed by Machado *et al*. (2011), using the equation:

$$Hdom = 17.4215 * exp(1 - 0.2285 * I)^{1.1438}$$

This equation presents statistics of fit and precision a $R^2aj = 0,64$ and a $Syx\% = 18,20$. To construct the site curves, the fitted equation was rearranged to estimate the values of the dominant height at different ages, resulting in the following expression:

$$Hdom = \frac{S * [1 - \exp(-0.2285 * I)]^{1.1438}}{[1 - \exp(-0.2285 * I_{ref})]^{1.1438}}$$

Where: Hdom = dominant height (m); S = Limit of the site curve at the reference age; I = Age (years); Iref = Reference Age (7 years).

The site classification resulted in 48 plots in class III, 190 in class II and 62 plots in class I, totaling 300 plots. Plots where *bracatinga* was not present, totaled 20 units and did not receive site classification.

Calculation of individual tree volumes:

For estimation of volumes of fire wood outside bark (stem + thick branches ≥ 4cm of diameter) of *bracatinga* trees, the volumetric equations fitted by Machado *et al*.(2008b) were used as described below:

- For DBH < 6 cm of diameter: $v = - 0.00232703*d + 0.000792859*d^2$; with $R^2aj = 0.9822$, and Syx% = 13.79.

- For DBH ≥ 6 cm of diameter: $\ln(v) = [- 9.79086 + 2.16699*\ln(d) + 0.752152*\ln(h)]*MCF$; with $R^2aj = 0.9923$, Syx% = 9.76 and MCF = 1.004393.

Where: ln = neperian logarithm; v = volume of fire wood outside bark (m^3); d = diameter at breast height (cm); h = total tree height (m); and MCF = Mayer correction factor.

Detection of discrepant data - "outliers":

An exploratory analysis was performed on the data base to detect the presence of discrepant values of volume per hectare for each sampled age. An observation whose value is much higher or much lower than the rest of the observations was considered as a discrepant data.

To reject discrepant data at each age, the quartile method was first used, with the rejection criterion for all values greater than 1.5 times the interquartile range from the 3rd quartile and less than 1.5 times the interquartile range from the first quartile. In the sequence, the data were plotted in graphs and observed its tendency. When values much higher or much lower were observed at different ages, they were also rejected.

Stand Volume Modeling:

Machado *et al*. (2008a), using 229 sample units from the data base of this study, modeled the volume of the stands for *bracatinga* in the metropolitan region of Curitiba. In that occasion, they tested 29 mathematical models selected from the forest literature, being 12 models of arithmetic nature, 4 semi-logarithmic and 13 logarithmic nature. Table 2 shows the arithmetic, semi-logarithmic and logarithmic models that were fitted.

Table 2: Mathematical models tested to estimate volumes of fire wood outside bark of *bracatinga* forests.

Nº	Mathematical model	Authors
1	$V = b0 + b1.G\bar{h} + b2.G + b3.\bar{h}$	STOATE (1945)
2	$V = b0 + b1.Gh_{dom} + b2.G + b3.h_{dom}$	
3	$V = b0 + b1.G\bar{h}$	SPURR (1952)
4	$V = b0 + b1.Gh_{dom}$	
5	$V = b0 + b1.G$	
6	$V = b0 + b1.G^2 + b2.G$	
7	$\ln(V) = b0 + b1.\ln(G\bar{h})$	
8	$\ln(V) = b0 + b1.\ln(G)$	
9	$\ln(V) = b0 + b1.\ln(G^2)$	
10	$\ln(V) = b0 + b1.\ln(G^2h_{dom})$	
11	$\ln(V) = b0 + b1.\ln(Gh_{dom})$	
12	$V = G\bar{h}/b0 + b1.d_g$	TAKATA (1959)
13	$V = b0 + b1.G^2$	MACHADO (1973)
14	$V = b0 + b1.G^2h_{dom}$	SILVA (1979)

To be continued…

Continuation.

15	$V = b0 + b1.\ln(G\bar{h})$	FIGUEIREDO FILHO (1983)
16	$V = b0 + b1.\ln(G^2\bar{h})$	
17	$V = b0 + b1.\ln(G)$	
18	$V = b0 + b1.\ln(G^2)$	
19	$\ln(V) = b0 + b1.\ln(G^2\bar{h})$	
20	$V = b0 + b1.G^2\bar{h}$	ROSOT (1989)
21	$\ln(V) = b0 + b1.\ln(GN)$	
22	$\ln(V) = b0 + b1.\ln(\bar{d}^2\bar{h})$	
23	$V = b0.G^{b1}.h_{dom}{}^{b2}$	UNG e OUELLETT (1991)
24	$V = b0.G^{b1}.\bar{h}^{b2}$	
25	$\ln(V) = b0 + \ln(G\bar{h})^{b1} + \ln(Gh_{dom})^{b2}$	
26	$\ln(V) = b0 + b1.\ln(G) + b2.\ln(\bar{h})$	
27	$\ln(V) = b0 + b1.\ln(G\bar{h}) + b2.\ln(Gh_{dom})$	
28	$\ln(V) = b0 + b1.\ln(G^2N)$	SCOLFORO (1997)
29	$\ln(V) = b0 + b1.\ln(N\bar{d})$	

Source: Machado *et al*. (2008a). Remodeled.
Legend: V = total volume outside bark per hectare (m³ / ha); G = basal area per hectare (m² / ha); h_{dom} = dominant height (m); dg = mean square diameter (cm); $\bar{d}$ = mean diameter at breast height (cm); N = number of trees per hectare; $\bar{h}$= mean total height (m); ln = neperian logarithm; *bi* = coefficients of the models.

Considering that the current database had a significant increase of sample units - from 229 to 278 - and with other ages included, that the individual volume of the trees was modeled and that the plots received site classification, the 29 models tested by Machado *et al*. (2008a) were again fitted to estimate the *bracatinga* stand volume, following the same criteria, but modifying the methodology used in the work of these authors, ie, added to the variable site in the selection process "forward stepwise" and the individual volume of trees was obtained with the equations developed by Machado *et al.*(2008b).

For the fit of linear arithmetic or logarithmic models, the least squares technique was used by simple or multiple linear regression; by the other hand the non-linear models were fitted by non-linear regression. It was also fitted other models considering the correlation among variables or using the method of fit by selection of variables called "forward stepwise".

Analyzes of fitted models:

For that the chosen equation have reliable estimates, the best among the tested was based on the following statistical criteria: the highest coefficient of determination (R²), the lowest standard error of estimate in percentage (Syx%), absence of multicollinearity and graphic analysis of residuals to verify heterocedasticity and biases present in the estimation.

The multicollinearity diagnosis was made informally by observing the non-significance (p value for α = 5%) of the coefficients of the independent variables used in multiple linear regression models, according to Scolforo (2005).

For equations fitted with the values of the dependent variable transformed to neperian logarithm, the estimated values were corrected to eliminate the logarithmic discrepancy and make them comparable with the arithmetic equations. In this case, the estimated volumes were multiplied by the Mayer Correction Factor – MCF (MCF = $e^{0,5*syx^2}$ where e = base of the neperian logarithms and Syx = standard error of the estimate in logarithm units) and then the R² and Syx were recalculated.

After choosing the best equation it was validated using the chi-square adherence test (□²) with a limit of α = 5% significance and graphical analysis of the residuals of the data used in the validation.

RESULTS AND DISCUSSION

Analysis of discrepant data:

As a result of the analysis of discrepant data for volume per hectare, from 300 plots containing *bracatinga*, 22 plots were outliers because they contained discrepant data. In this way, 278 plots were left which were used for the volumetric modeling processes of the sampled stands. Figure 01 shows the before and after the removal of the discrepant data.

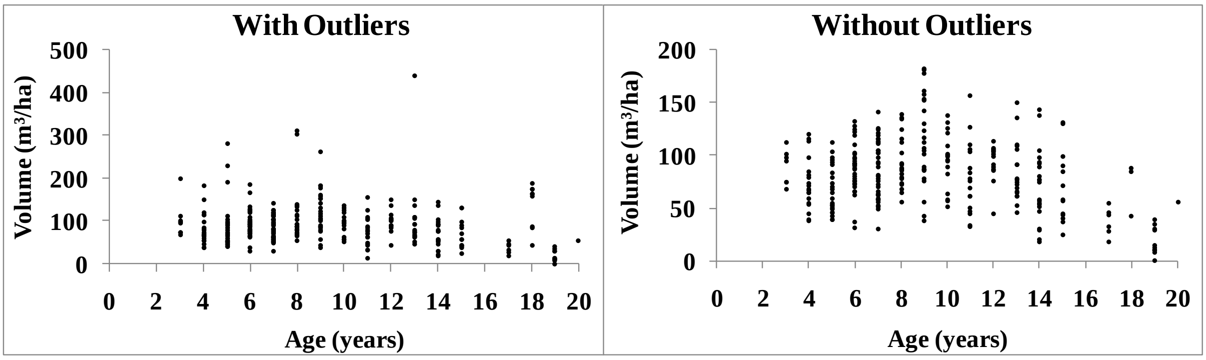

Fig. 1: Volume values per hectare for the plot with *bracatinga* throughout the ages, before and after the removal of outliers.

Descriptive statistics of the main variables used in the fit of models:

After the discrepant data were extracted, the descriptive statistics of the main variables used in stand volume modeling were calculated. These statistics are shown in Table 3.

Table 3: Descriptive statistics of the main variables used for fit of models.

Variable	Minimum	Mean	Maximum	Standard deviation	CV %
Age of *bracatinga* - I (anos)	3.0	9.3	19.0	4.1	43.6
Number of Trees per Hectare – N	50	1721	11584	1580	91.8
Mean Diameter at Breast Height - $\bar{d}$ (cm)	3.7	10.9	25.1	3.9	35.4
Mean Total Height - $\bar{h}$ (m)	5.0	12.3	20.2	2.6	21.3
Mean Square Diameter - dg (cm)	4.1	11.3	25.3	4.0	35.1
Site - S (m)	9.0	13.0	17.0	2.4	17.8
Dominant Height - h_{dom} (m)	5.0	13.6	21.3	2.8	20.6
Basal Area per Hectare - G (m²)	1.2	11.3	24.5	4.3	37.9
Volume per Hectare - V (m³)	7.9	81.8	182.1	33.4	40.9

Correlation among variables used for the fit of models:

After exploratory analysis of volumetric data and removal of plots with discrepant values, the analysis of simple linear correlation between the independent (measured, calculated, combined and transformed) and the dependent variables (wood volume per hectare in arithmetic and logarithmic form). Table 4 shows the correlation values between the 63 independent variables analyzed with the 2 dependent variables.

Table 4: Simple linear correlation coefficient of the independent variables with the dependent variables.

Independent	Dependent Variables		Independent	Dependent Variables		Independent	Dependent Variables	
Variables	V	ln(V)	Variables	V	ln(V)	Variables	V	ln(V)
I	-0.250	-0.370	GN	0.265	0.296	$\ln(G^2N)$	0.632	0.743
N	0.146	0.217	G^2N	0.320	0.319	$\ln(\bar{d}^2\bar{h})$	0.121	0.030
$\bar{d}$	-0.031	-0.127	$\ln(\bar{d})$	0.030	-0.076	$\ln(N\bar{d})$	0.549	0.665
$\bar{h}$	0.372	0.338	$\ln(\bar{h})$	0.388	0.364	$1/\bar{d}$	-0.080	0.027
dg	-0.021	-0.117	$\ln(h_{dom})$	0.449	0.449	$1/\bar{h}$	-0.393	-0.384
S	0.478	0.494	ln (dg)	0.038	-0.069	$1/h_{dom}$	-0.430	-0.454
h_{dom}	0.450	0.431	ln(G)	0.821	0.913	1/dg	-0.087	0.022
G	0.859	0.845	$Ln(\bar{d}\bar{h})$	0.180	0.100	1/G	-0.650	-0.849
$\bar{d}\bar{h}$	0.122	0.054	$Ln(\bar{d}^2\bar{h})$	0.121	0.030	$1/\bar{d}\bar{h}$	-0.210	-0.129
$\bar{d}^2\bar{h}$	0.008	-0.054	$Ln(\bar{d}h_{dom})$	0.217	0.142	$1/\bar{d}^2\bar{h}$	-0.166	-0.081
$\bar{d}h_{dom}$	0.175	0.108	$Ln(\bar{d}^2h_{dom})$	0.142	0.053	$1/\bar{d}h_{dom}$	-0.235	-0.163
$\bar{d}^2h_{dom}$	0.044	-0.021	$\ln(G^2)$	0.821	0.913	$1/\bar{d}^2h_{dom}$	-0.180	-0.096
G^2	0.823	0.745	$\ln(G\bar{h})$	0.920	0.996	$1/G^2$	-0.450	-0.689
$G\bar{h}$	0.994	0.929	$\ln(G^2\bar{h})$	0.893	0.978	$1/G\bar{h}$	-0.656	-0.871
$G^2\bar{h}$	0.946	0.825	$\ln(Gh_{dom})$	0.904	0.985	$1/G^2\bar{h}$	-0.439	-0.688
Gh_{dom}	0.979	0.917	$\ln(G^2h_{dom})$	0.883	0.971	$1/Gh_{dom}$	-0.634	-0.855
G^2h_{dom}	0.936	0.818	$\ln(dg\bar{h})$	0.187	0.106	$1/G^2h_{dom}$	-0.432	-0.682
$dg\bar{h}$	0.131	0.062	$\ln(dg^2\bar{h})$	0.129	0.037	$1/dg\bar{h}$	-0.218	-0.136
$dg^2\bar{h}$	0.020	-0.043	$\ln(dgh_{dom})$	0.223	0.149	$1/dg^2\bar{h}$	-0.177	-0.089
dgh_{dom}	0.184	0.116	$\ln(dg^2h_{dom})$	0.150	0.060	$1/dgh_{dom}$	-0.243	-0.170
dg^2h_{dom}	0.056	-0.009	ln(GN)	0.549	0.665	$1/dg^2h_{dom}$	-0.191	-0.104

Where: V = volume of firewood outside bark in m³/ha; Ln (V) = neperian logarithm of the volume of firewood outside bark in m³/ha; I = Age of *bracatinga* (years); N = Number of trees per hectare; $\bar{d}$= Mean diameter at breast height (cm); $\bar{h}$= Mean of total height (m); dg = Mean square diameter (cm); S = Site index (m); h_{dom} = Dominant height (m); and G = basal area per hectare (m²).

It is observed that the variables measured in the plot did not directly correlate well with the two volumetric variables; meanwhile the variable basal area (which is easily calculated based on the diameters measured in the field in fixed area plots) showed a good correlation with the volumetric variables (R = 0.85). A similar result was observed by Machado *et al.* (2008b), whou mentioned that the pure variables, with the exception of basal area, presented low correlation with the dependent variable, but when combined showed high correlations.

Figueiredo Filho *et al.* (1982), modeling the volume per unit of area in tropical forests state that basal area (G) is a very important variable for evaluation of volume per unit of area, due to the facility of its measurement and the high degree of correlation with volume of the stand. The combinations of basal area with the variables mean height and dominant height were those that resulted in the highest correlations.

The highest simple linear correlation (r) of wood volume per hectare, outside bark, (V) was with the combined variable of the basal area and mean total height ($G.\bar{h}$), with r = 0.994, followed by the combined variable basal area and dominant height ($G.h_{dom}$), with r = 0.979. For the variable ln(V), the highest correlation was with the variable $\ln(G.\bar{h})$, that presented a r = 0.996 followed by the variable $\ln(G.h_{dom})$, that presented r = 0.985. These results were similar to those observed by Machado *et al.*, (2008a), that presented with details, the relationships between the various variables measured, calculated, combined and transformed that were used in the modeling of the *bracatinga* stand volume.

Souza *et al.* (2013), modeling the organic carbon per hectare for the *bracatinga* and Souza *et al.* (2014), modeling aerial biomass per hectare of *bracatinga*, observed in both researches that, the most correlated variables were those with the basal area combined with the mean diameter and with quadratic diameter. This result differs from those traditionally found in the literature and with that observed in Table 4.

Adjustment of models:

Out of the 278 plots remaining after removal of outliers, they were used 230 plots for volume modeling of *bracatinga* stands and 48 plots, covering the range of variation of ages and sites, for validation of the equation with the best performance.

For the 29 fitted models selected from the forest literature, the standard errors of estimate in percentage (Syx%) ranged from 3.99% to 40.88% (with the best 12 presenting error less than 10%); The coefficients of determination (R^2aj) ranged from 0.991 to 0.0. The results of the fit and precision statistics for the 29 models can be seen in Table 5.

Table 5: Coefficients of the fitted equations and their respective statistics of fit and precision.

Model	b0	b1	b2	b3	MCF	R²aj	Syx	Syx%
12	1.7305	0.1882	----	----	----	0.991	3.2654	3.99
1	6.0036	0.6125	-0.3288	-0.4139	----	0.990	3.4078	4.17
3	1.1675	0.5837	----	----	----	0.990	3.4264	4.19
24	0.6368	0.9968	0.9740	----	----	0.989	3.4357	4.20
25	-0.5692	0.9970	-1.6596	----	1.0010	0.989	3.5216	4.31
27	-0.2927	0.8918	0.0602	----	1.0010	0.988	3.6331	4.44
7	-0.2980	0.9544	----	----	1.0010	0.988	3.6362	4.45
26	-0.2646	0.9575	0.9380	----	1.0010	0.988	3.6447	4.46
4	4.3798	0.5004	----	----	----	0.963	6.4636	7.90
2	1.2105	0.4737	0.3911	0.2119	----	0.962	6.4789	7.92
23	0.7024	0.9555	0.9338	----	----	0.962	6.5327	7.99
11	-0.1322	0.9005	----	----	1.0033	0.960	6.7069	8.20
19	0.7291	0.4995	----	----	1.0057	0.931	8.7643	10.71
10	0.8023	0.4823	----	----	1.0074	0.912	9.9139	12.12
20	36.2587	0.0257	----	----	----	0.895	10.8517	13.27
14	36.9596	0.0225	----	----	----	0.880	11.5945	14.17
15	-193.88	57.25	----	----	----	0.838	13.4467	16.44
16	-130.28	29.68	----	----	----	0.793	15.2161	18.60
5	5.3757	6.7606	----	----	----	0.749	16.7407	20.47
6	3.5462	-0.0169	7.1405	----	----	0.748	16.7724	20.50
9	2.0724	0.4778	----	----	1.0218	0.749	16.7631	20.49
8	2.0724	0.9556	----	----	1.0218	0.749	16.7631	20.49
13	40.7576	0.2810	----	----	----	0.698	18.3677	22.45
17	-48.971	56.152	----	----	----	0.677	18.9955	23.22
18	-48.971	28.076	----	----	----	0.677	18.9955	23.22
28	1.9025	0.2047	----	----	1.0602	0.315	27.6834	33.84
29	-0.2626	0.4863	----	----	1.0759	0.182	30.2521	36.98
21	2.0294	0.2420	----	----	1.0757	0.180	30.2902	37.03
22	4.1668	0.0183	----	----	1.1410	0.000	33.4427	40.88

Legend: *bi* = coefficients of the fitted equations; MCF = Mayer correction factor; R^2aj = fitted coefficient of determination; Syx = Standard error of estimate.

In stand volume modeling with *bracatinga* sampled plots, it is observed that the equations whose variable of the highest correlation ($G.\bar{h}$) is present, were the ones that present a better performance. Ribeiro *et al.* (2012), modeling the amount of nutrients per hectare in *bracatinga* forests, observed that the best models were those that had the combination of basal area with the mean height and/or dominant height, highlighting model 26 from Ung and Ouellett (1991), the model 19 from Figueiredo Filho (1983), and the model of the best performance from Machado *et al*. (2008a) obtained by the stepwise process.

Out of the 29 selected models from the forest literature, stood out the model 12 of Takata (1959) with Syx% = 3.99 and R²aj = 0.9905, followed by the equation fitted for the model 1 of Stoate (1945), with Syx% = 4,17 and R² = 0.9896, and by the fitted equation for the model 3 of Spurr (1952), with Syx% = 4.19 and R² = 0.9895. The graphical distribution of residuals from the 3 best equations are shown in Figure 2.

In the work from Machado *et al*. (2008a) these same arithmetic equations were the ones of better fits, but in order of performance stood out the model 1, in second place was the model 3 and thirdly the model 12; according to these authors, the logarithmic equations were better than the arithmetic ones, standing out the models 7 of Spurr (1952) and models 25, 26 and 27 of Ung and Ouellett (1991). Working with modeling of stand volume in natural forests of the county in Viçosa, Minas Gerais, Oliveira *et al*. (2005), observed that the best fitted equation to estimate the stand stem volume was the logarithmized model 25 of Ung and Ouellett (1991) and to estimate the total stand volume was the non-linear model 24 of Ung and Ouellett (1991); In this work models 24 and 25 were in 4th and 5th place in order of performance, respectively.

Souza *et al*. (2014), modeling the biomass of *bracatinga* in native stands and Cysneiros *et al*. (2016) modeling the volume of Ombrophilous forest in the Amazon, selected the Spurr combined variable model (Model 7) as one of the most efficient for estimating the production of firewood per unit of area; and for the exploitable volumetric production in the Amazon rainforest, respectively. In this work, the equation of this model ranked 5th in general performance, with a standard error of 0.45% higher than the first one.

The variable dg presented a low correlation with the volumetric variables, both in the arithmetic and logarithmic forms, as can be seen in Table 4. However, since the variable dg in model 12 generated a gain in the composition of the equation, it was decided to add this variable in logarithmic form to model 27, which was then denominated model 30. An arithmetic and a logarithmic equation was also fitted by the Forward Stepwise process, which were denominated equations 31 and 32 respectively. These models are presented below with their respective coefficients. Its fit and precision statistics are presented in Table 6 as well as the graphical distribution of residuals shown in Figure 2.

Equation 30: $\ln(V) = -0.4828 + 0.7581*\ln(G.\bar{h}) + 0.1938*\ln(G.h_{dom}) + 0.0746*\ln(dg)$
Equation 31: $V = 9.7058 + 0.4753*G.\bar{h} - 117.6027*dg^{-1} + 1.6026*G$
Equation 32: $\ln(V) = -0.1895 + 0.9848*\ln(G.\bar{h}) - 0.0107*h_{dom} - 1.1001*dg^{-1}$

Table 6: Fit and precision statistics of equations 30,31 and 32, ordered according to Syx%.

Model	MCF	R²aj	Syx	Syx%
31	----	0.9948	2.4084	2.94
32	1.0006	0.9929	2.8267	3.46
30	1.0007	0.9917	3.0421	3.72

Table 6 shows for equations 30, 31 and 32 their fit and precision statistics. In the process of fit these equations, it was observed that they did not present a multicollinearity problem between the variables, and their coefficients were significant at 95% of probability.

Observing the fit and precision statistics in Table 6, it can be seen that the equation 31 (logarithmic) fitted by the process "Forward Stepwise" resulted as the one of better performance, when compared to equations 30 and 32 and also whit the 29 models taken from the forest literature.

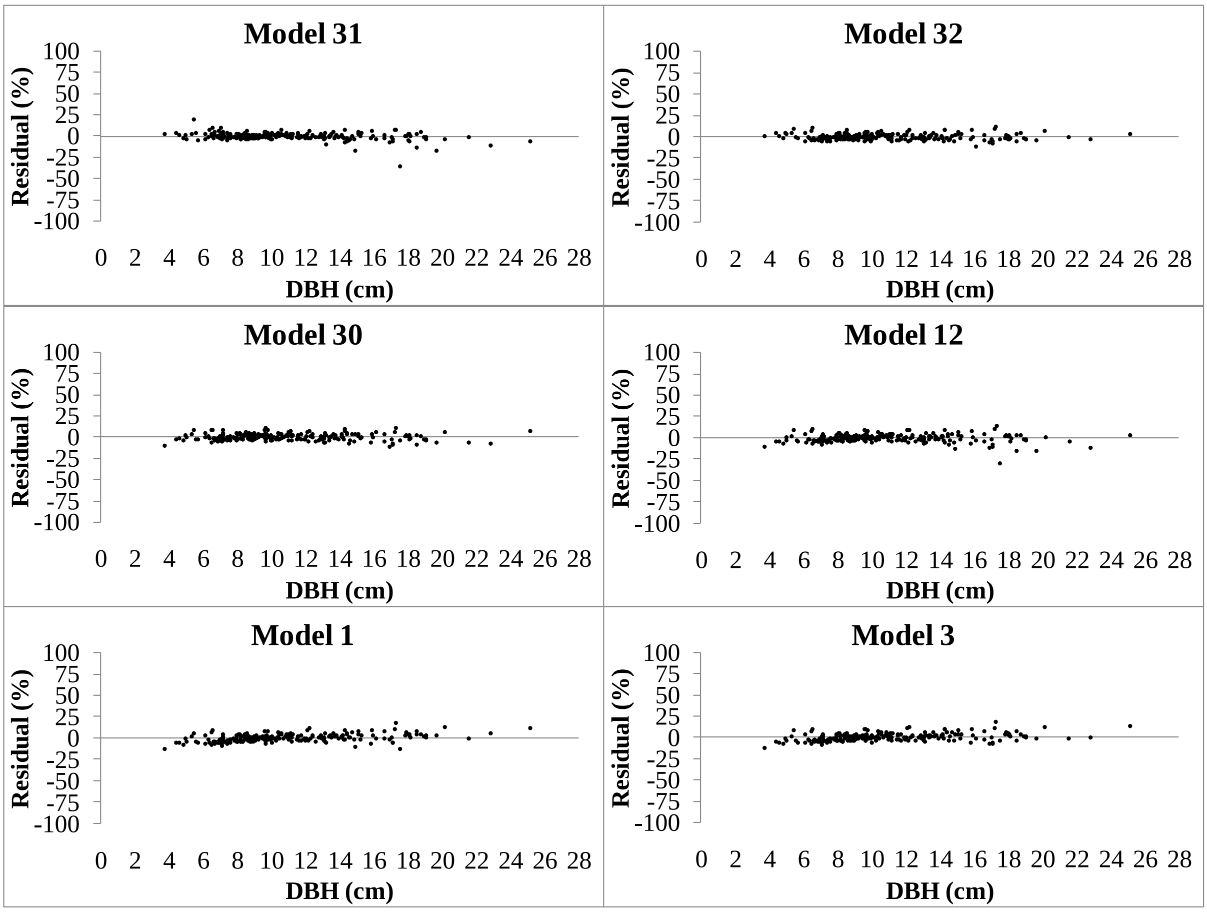

Fig. 2: Graphics of residuals for the 6 best equations fitted to estimate the volume per hectare of the *bracatinga* forests.

It is observed in Tables 5 and 6, small differences between the fit and precision statistics of models 1, 3 and 12 and equations 30, 31 and 32. Analyzing the graphics of residuals in Figure 2, it can be seen that equation 31 has slightly larger data dispersion than equations 30 and 32 and that the equations from models 1, 3 and 12 have a small of overestimate bias at the lowest ages and underestimate bias at the oldest ages. The residuals of equations 30 and 32 are homogeneous along the whole diameter distribution. The percent residuals in equation 30 had their extremes at -11.31 and 10.70 with a mean of -0.25 and a variance of 14.6; the residuals of equation 32 had their extremes at -11.90 and 12.38 with a mean of -0.21 and a variance of 12.29. Thus, it is verified that equation 32 has a more homogeneous distribution of residuals than the others, being therefore the one chosen for the validation process.

Machado *et al.* (2008a), fitted arithmetic, logarithmic and semilogarithmic equations by the "Stepwise" process, and selected as the best one the arithmetic equation, whose formula is: “$V = 0.23415 + 0.40208*G.\bar{h} + 0.09969*G.h_{dom}$” with Syx% = 2.07 and $R^2 = 0.997$. This equation was validated at the time, and recommended for use for the *bracatinga* forests of the metropolitan region of Curitiba.

In this way, equation 32 and the equation recommended by Machado *et al.* (2008) were submitted to the validation process. In the validation process the Chi-square test (²), for equation 32, presented a calculated value (²cal = 6.20) which is lower than the table value (²tab (α = 5%) = 64.00) that is, there is no statistical difference between the estimated and table values. However, the equation recommended by Machado *et al.* (2008), presented a calculated value (²cal = 101.75), thus higher than the table value, having a significant statistical difference between the observed and estimated values. The standard error of the estimate (Syx%), recalculated with the validation data for both equations, presented for equation 32 a value equal to 4.16% and for the equation recommended by Machado *et al.* (2008a) a value equal to 16.1%. The fact that the equation recommended by Machado *et al.* (2008a) have been validated at the time of its fit, and but not in the present research. This can be explained simply due to the change of the database, to adittion of more plots including older ages and also by the change of methodology for calculating individual volumes.

Figure 3 shows the dispersion of the residual values obtained with the estimation of the total volume per hectare of the *bracatinga* for the data used in the validation of the equation 32, evidencing the homogeneous distribution throughout the regression line.

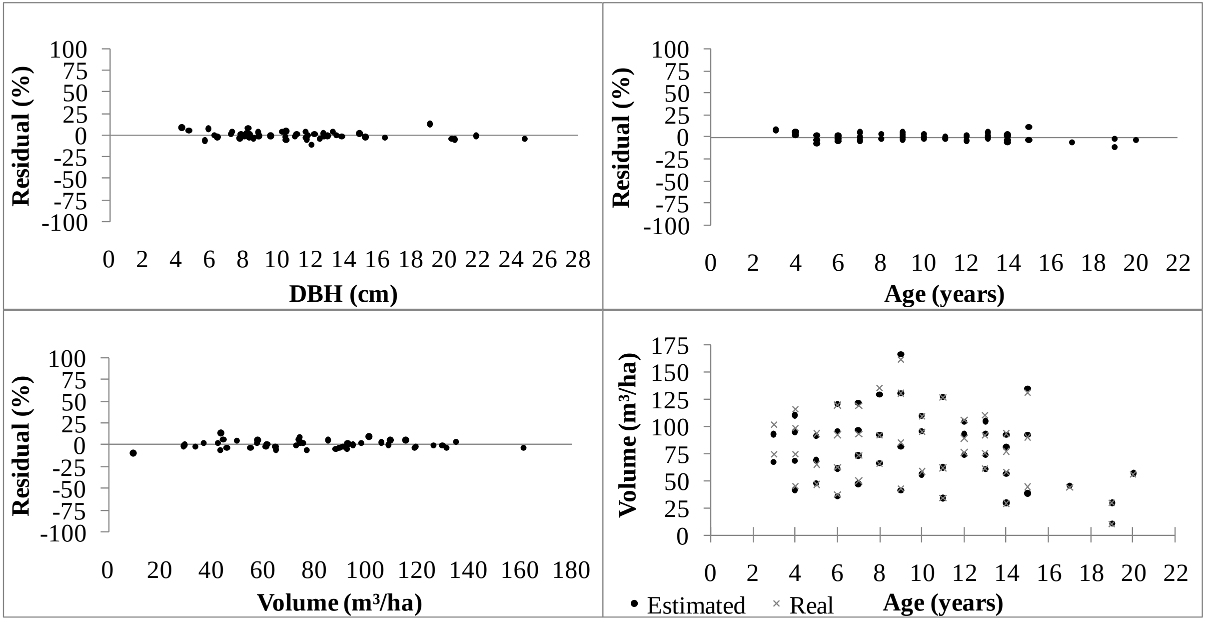

Fig. 3: Graphics of residuals and distribution of used data to validate the best fitted equation to estimate volume per hectare of *bracatinga* forests.

Conclusions:

The obtaintion of estimated stand volume through models by unit of area is an accurate and faster than the traditional method of estimation using the volume per individual tree and is therefore advantageous due to field work reduction, and data processing, consequently resulting in lower cost of the forest inventory.

To estimate the volume per hectare of the *Mimosa scabrella* Benth (bracatinga) in the bracatinga forests, among the 29 models taken from the literature, the non-linear equation corresponding to the model 12 of Takata (1959) was the one that presented the best result. The equation fitted by the forward stepwise process with the best result was the logarithmic one. Between these two equations there is a small difference regarding the standard error of estimate.

The use of the process of variable selection by means of the forward stepwise methodology resulted in equations with higher levels of precision and fit than the equations fitted using models from the literature.

The validation test shown no statistical difference between the actual and estimated volumes, enabling the logarithmic equation obtained through the forward stepwise method for use in the processing of the inventories of *bracatinga* in the stands of the metropolitan region of Curitiba.

The fact that the equation recommended by Machado *et al.* (2008a) have been validated at the time of its fit, and but not in the present research. This can be explained simply due to the change of the database, to adittion of more plots including older ages and also by the change of methodology for calculating individual volumes.

For the use of the equation of better performance it is necessary only to obtain the mean height, dominant height and diameter of the trees and posterior calculation of the basal area and mean square diameter.

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