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Methods of estimation of total volume of a hybrid of Eucalyptus

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ABSTRACT

The accuracy of volumetric estimates plays influence on reliability of the volumetric assessments per unit of area, constituting in one of the main phases of these forest surveys. The objective of this study was to apply methods to estimate the total bole volume of a hybrid of eucalyptus, considering the more precise estimates regarding to Huber's volume calculation, taken as the real volume. Four methodologies were used; two of them were subdivided into two cases each, resulting in six options, namely: using the quadratic diameter directly in the volume equation (methods 1a and 1b), using the quadratic diameter through regression estimation (methods 2a and 2b), using relative height (method 3) and using the Schumacher-Hall model (method 4). The choice of the best method was made by graphical analysis of residuals, *Syx* (%), *CV,* bias (*V*), mean differences (*MD*) and standard deviation of the differences (*DPD*). By results, the traditional model of Schumacher-Hall for total volume was the most accurate, followed by methods 1b and 2b, which are based on quadratic diameter (dq^2) in regression models, having as independent variables *dq* and dq^2.

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INTRODUCTION

The forest sector has consolidated itself as one of the most profitable in the Brazilian economy, not only from the point of view of sawn wood, but also in pulp, paper and coal production, in addition to carbon credits, when it refers to standing forest.

The great emphasis should be given to planted forests, which cover a large part of the economic, social and environmental scenario of the country. According to the Brazilian Association of Planted Forests (ABRAF, 2012), the planted forest area in Brazil in the year 2011, reached to 6.52 million hectares, of which 4.9 million hectares are planted with the genus *Eucalyptus*.

Among the factors that favor the planting of this genus are: the rapid growth in short rotation cycle, high forest productivity, expansion and the targeting of new investments by companies that use wood as a raw material in industrial processing. The genus *Eucalyptus* is used for a large variety of purposes, such as: wood, charcoal, pulp, railroad ties, poles for electricity transmission, bark for tanning leather, essential oils and civil construction (Lima, 1993).

Today, Brazil is ranked as one of the largest producers of Eucalyptus in the world. For this reason, in order to quantify the raw materials and production in planted and native forests, a forest inventory is carried out so that industries or owners can get more reliable and precise volumetric estimates from their areas. Consequently, the choice of models or methods of volumetric estimates is an important phase of the forest inventory, once that trend in the total or partial volume estimated will bring reflections on estimates for the total population, causing a sub- or super evaluation of the production (Scolforo, 2005).

Still, according to Figueiredo (1982), the accuracy of volumetric estimates plays influence on reliability of the volumetric assessments per unit of area, constituting in one of the main phases of these forest surveys. These

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volumetric estimates can be made using direct traditional methods, as the xilometer, and indirect, such as cubic scaling of trees, in absolute and relative ways, for estimation using total volume equations, taper functions, and functions of volumetric ratios. Other methodologies consist in estimation using the mean diameter square proposed by Péllico Netto (1979) and the relative height suggested by Andrade and Leite (2001), Leite and Andrade (2002; 2004).

The objective of this research was to test different methods to estimate the total bole volume of the hybrid of *Eucalyptus grandis* W. Hill ex Maiden with *Eucalyptus urophylla* S. T. Blake.

MATERIAL AND METHODS

Characterization of the Site:

The data for this study were collected in Federal Institute of Education, Science and Technology of the state of Minas Gerais (IFMG) - Campus Sao Joao Evangelista, located in the municipality of Sao Joao Evangelista, in Minas Gerais state. The average altitude at the Campus is 452 meters above sea level, average temperature of 22º C with annual maximum of 26.1º C and with minimum of 15º C. The average annual rainfall is 1,081 mm. The climate classification according to Köppen is Cwa with dry winter and summer with rainy season.

Rigorous cubing of the bole:

The measurements were carried out in an area of 3.48 hectares planted with the hybrid Eucalyptus grandis x Eucalyptus urophylla from clone propagation, established with spacing of 3 x 2 meters, with 8 years of age. Sixty six trees were climbed (Table 1), with dbh that ranged from 4.5 to 32.6 cm and total height (ht) between 8.68 to 31.79 m.

Table 1: Frequency Distribution of trees by *dbh* and height classes.

Height Classes (m)	*dbh* classes (cm)							Total
	0 - 4.9	5 - 9.9	10 - 14.9	15 - 19.9	20 - 24.9	25 - 29.9	30 - 35.0	
8.0 - 9.9		2						2
10.0 - 11.9	1	2						3
12.0 - 13.9		2	1					3
14.0 - 15.9		2						2
16.0 - 17.9		3	3					6
18.0 - 19.9			3					3
20.0 - 21.9			1	1				2
22.0 - 23.9			1					1
24.0 - 25.9			2			1		3
26.0 - 27.9				4	1	3	6	14
28.0 - 29.9				7	6	5	1	19
30.0 - 32.0					5	3		8
Total	1	11	11	12	12	12	7	66

To compose the database used in all the adjustments proposed in the present work, we measured the values of *di* (diameter measured at the height *hi*) using the methodology of Hohenadl's relative height, in which the tree was subdivided into ten sections of equal size and diameters measured on the half of each section, i.e., at 5 %, 15 %, 25 %, 35 %, 45 %, 55 %, 65 %, 75 %, 85 % and 95% of the total tree height (Figure 1). The actual volume of each tree was obtained by adding the partial volumes obtained along the bole (Figure 1).

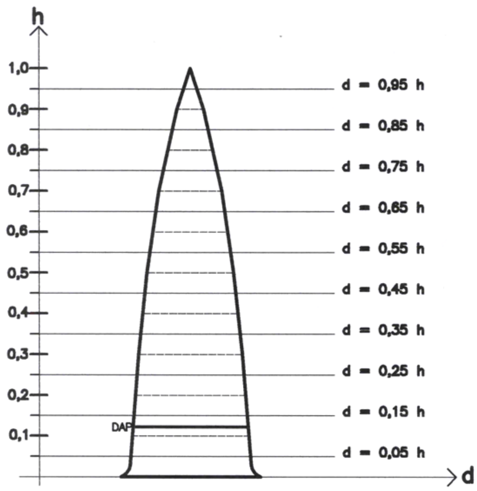

Fig. 1: Schematic drawing used for measurement of the diameters by Hohenadl's method.

Methods Used For Estimation of The Total Volume:

Method using the quadratic diameter - Method 1:

This method, applied the first time in Brazil by Figueiredo (1982), estimates the volume based on the methodology of Hohenadl (1924) as cited by Prodan (1965), which divides the bole in five parts of equal length. However according to Prodan (1965), the smaller the length of the sections, closest are the estimated volumes of the exact ones. Thus, we choose to divide the bole in ten sections of relative length to increase accuracy of the estimates (Figure 1).

To determine the relationship between the natural and artificial form factor, Ko (1968) introduced the following concept on the quadratic diameter (d_q^2), considering the natural form factor calculated using Hohenadl's method:

$$f_{0,05} = \frac{1}{d_{0,05}^2}\left(\frac{d_{0,05}^2 + d_{0,15}^2 + d_{0,25}^2 + d_{0,35}^2 + d_{0,45}^2 + d_{0,55}^2 + d_{0,65}^2 + d_{0,75}^2 + d_{0,85}^2 + d_{0,95}^2}{10}\right) \quad (1)$$

Where inside the parentheses we get the mean quadratic of diameters of the series, i.e.:

$$d_q^2 = \frac{d_{0,05}^2 + d_{0,15}^2 + d_{0,25}^2 + d_{0,35}^2 + d_{0,45}^2 + d_{0,55}^2 + d_{0,65}^2 + d_{0,75}^2 + d_{0,85}^2 + d_{0,95}^2}{10} \quad (2)$$

The Hohenadl's form factor will be then obtained as:

$$f_{0,05} = \frac{d_q^2}{d_{0,05}^2} \quad (3)$$

This concept of form factor was enlarged by Ko (1968) using the expression (4), which uses a reference diameter taken to determine any form factor desired, provided that the diameters are taken from a relative series:

$$f_{0,x} = \frac{0,1\sum d_{0,i}^2}{d_x^2} \quad (4)$$

Where: d_x = reference diameter and $d_{0,i}$ = measured diameters in each of the sections.

Taking the mean quadratic diameter as reference, we get the form factor equal to one (Prodan, 1965).

$$f_q = \frac{d_q^2}{d_q^2} = 1 \quad (5)$$

The form of the tree, in this case, is equivalent to a cylinder whose diameter is coincident with the mean quadratic diameter. In this way, the volume is obtained as follows:

$$v = \frac{\pi}{40000} d_x^2 .h.f_x \quad (6)$$

Using the form factor equal to one, there is a simplification to obtain the equivalent tree volume to that of a cylinder whose base is d_q:

$$v = \frac{\pi}{40000} d_q^2 h \quad (7)$$

Considering the operations and replacements as seen in the procedure proposed by Prodan, the default volume for the bole can be obtained as:

To compose the method (1), we sought to establish a relationship between the mean quadratic diameter (d_q^2) with *dbh*, which is the variable of easier measurement in the forest, i. e., d_q^2 can be estimated through regression equations adjusted as function of $d_{0.05}$ or the *dbh*.

Ko (1968) sought to relate the mean quadratic diameter (d_q^2) or (d_q) with the *dbh*. He proposed initially the solution using a straight line as follows:

$$dq = \beta_0 + \beta_1 d_{1.30} + \varepsilon_i \quad (8)$$

Or using parables

$$d_q^2 = \beta_0 + \beta_1 d_{1,30}^2 + \varepsilon_i \qquad (9)$$

$$d_q^2 = \beta_0 + \beta_1 d_{1,30} + \beta_2 d_{1,30}^2 + \varepsilon_i \qquad (10)$$

Where: β_0, β_1 and β_2 = coefficients of the models.

Substituting the result obtained in (8), after squaring it, (9) or (10) in (7) you can get the tree volumes as suggested by Ko (1968), and in this case, by the methods 1a and 1b, respectively.

The adjustments were performed using the procedure of linear regression and the parameters had its significance tested by t-test, at 95% of probability level. To check the reliability of these adjusted models the statistics Syx (%) and the adjusted coefficient of determination (R^2) were obtained.

Method using the mean quadratic diameter in volumetric regression - Method 2:

Péllico Netto (1979) has proposed expanding the solution suggested by Ko (1968) in a direct application of a volumetric function solved by linear regression using the models (15) and (16). Under these conditions you have:

$$V = \frac{\pi}{4}\left(a + b.d_{1,30}^2\right) h$$

$$V = \left(\beta_0 + \beta_1 d_{1,30}^2\right) h + \varepsilon_i \quad \text{or} \qquad (11)$$

$$V = \left(\beta_0 + \beta_1 d_{1,30} + \beta_2 d_{1,30}^2\right) h + \varepsilon_i \qquad (12)$$

Note that the regressions can be easily adjusted using the transformation *V/h*, which is essentially equivalent to the estimation of d_q^2 multiplied by a constant, i.e.:

$$\frac{V}{h} = \beta_0 + \beta_1 d_{1,30}^2 + \varepsilon_i \quad \text{or} \qquad (13)$$

$$\frac{V}{h} = \beta_0 + \beta_1 d_{1,30} + \beta_2 d_{1,30}^2 + \varepsilon_i \qquad (14)$$

In adjustments made with trees of larger sizes, the equations (13) and (14) result in solutions with low random errors and high value of the coefficient of determination, however, when the estimates of Hohenadl are done in small trees, the authors found that the effect of density is still significant in diameter taken at 1.30 m, then the coefficient β_0 displays trends in these circumstances. It is suggested, therefore, that the models (13) and (14) are adjusted without its participation, which makes the equation (13) a ratio, in which the coefficient β_1 passes to exercise the function of a form factor, method at work called 2a and, in the case of equation (14), method 2b.

The adjustments were performed using the procedure of least square linear regression and the parameters had its significance tested by t-test, at 95% of probability level. To check the reliability of these adjusted models the statistics *Syx*(%) and the coefficient of determination adjusted (R^2) were obtained.

Method of relative height - Method 3:

In this method, developed by Andrade and Leite (2001), adjusted and modified by Leite and Andrade (2002; 2004), the volume of a tree is estimated by mathematical procedure which involves calculating the slope or the angular coefficient of the straight line that passes between 1.30 m and a relative height (h_r), and also between hr and h_t, employing the following expressions, respectively.

$$\mu_I = \frac{1,3 - h_r}{(dap - d_{hr})/2} \qquad (15)$$

$$\mu_{II} = \frac{h_r - h_t}{(d_{hr} - 0)/2} \qquad (16)$$

Where μ_I and μ_{II} are the angular coefficients of straight lines formed, respectively, in the intervals between 1.30 m and h_r, and between h_r and h_t.

As presented by Leite and Andrade (2004), the d_{hr} (diameter at relative height) was obtained or estimated at the corresponding *hr* by the expression:

$$h_r = (h_t - 2)/2 \tag{17}$$

The values of *hr* and *dhr* were used to estimate the angular coefficients by the expressions (15) and (16) on each tree. With the data resulting from the angular coefficients, and with *dbh* and *ht*, the following model was adjusted with *j* = *I* and *II*:

$$\mu_j = \beta_0\, dap^{\beta_1}\, ht^{\beta_2} + \varepsilon_i \tag{18}$$

The equation set was replaced in the expressions (15) and (16), according to Leite and Andrade (2002), and represent an expression of taper, estimating the diameters from the following equations:

$$d_I = \frac{2h - 2{,}6}{\bar{u}_I} + dap \tag{19}$$

$$d_{II} = \frac{2h - 2Ht}{\bar{u}_{II}} \tag{20}$$

Where d_I and d_{II} are the diameters at the desired height h; $\bar{\mu}_j = \frac{1}{n}\sum_{i=1;j=1}^{n,H} \mu_j$ and *n* is the number of trees.

These expressions were used to estimate the diameter in sections obtained by Hohenadl's method, diameters calculated from section 0.0 to *hr* by *dI* and *hr* until the total height was used as an average between the values obtained in *dI* and *dII*.

The volume estimation by this method was made using the Smalian methodology

Method using the Schumacher-Hall model - Method 4:

To test the accuracy of the five methods described in previous sections, we have selected the Schumacher-Hall model (1933), the most accurate model used to estimate volume in eucalyptus plantations:

$$V = \beta_0 dap^{\beta_1} ht^{\beta_2} + \varepsilon_i \tag{21}$$

Where: *dbh* = diameter with bark measured the height of 1.30 m; *ht* = total height; β_i = parameters of the fitted model (*i* = 0, 1, 2, ... , *n*), *V* = total volume of each tree.

The adjustments were performed using non linear regression with the iterative method proposed by Gauss-Newton and the parameters were evaluated by t-test at 95% probability level. To check the reliability of these adjusted models the statistics *Syx* (%) and adjusted coefficient of determination (R^2) were obtained.

Analysis of The Quality of Volume Estimates:

The results of estimated volumes obtained in the different methods were compared with the volume obtained by Huber's method.

To evaluate the accuracy of the estimates and choose the best method of adjustment for data, comparisons were made through the statistics, coefficient of variation (*CV*) and standard error of estimate *Syx* (%).

First, a graphic analyzes of residuals was performed. Residual values used in the graphics are expressed by:

$$Residuals(\%) = \frac{(Y - \hat{Y})}{Y} 100 \tag{22}$$

Where: $\hat{Y} =$ volumes estimated by different methods; $Y =$ values obtained by applying the Huber's method.

To complement the graphical analysis of residuals, additional tests were performed by means of the following statistics: *bias* (*V*); average of absolute differences (*MD*) and standard deviation of the differences (*DPD*) that are presented in (29), (30) and (31), as used by Lima (1986), Mendonça *et al*. (2007), de Souza (2008), Môra (2011). From the analysis of the statistics *V*, *MD* and *DPD,* it was proceeded the ordination of the methods according to the greater or lesser degree of accuracy, being assigned weights of 1 to 6, according to the results of the statistics obtained for each method.

$$V = \frac{\sum_{i=1}^{n} Y_i - \sum_{i=1}^{n} \hat{Y}_i}{n} \tag{23}$$

$$MD = \frac{\sum_{i=1}^{n} \left| Y_i - \hat{Y}_i \right|}{n} \tag{24}$$

$$DPD = \sqrt{\frac{\sum_{i=1}^{n} d_i^2 - \frac{\left(\sum_{i}^{n} di\right)^2}{n}}{n-1}} \tag{25}$$

Where: *Yi* = total volume calculated (m³); $\overset{\wedge}{Y_i}$ = estimated value by tested methods (m³); *n* = number of observations; and $d_i = Y_i - \hat{Y}_i$

For the choice of the more accurate equation, the isolated analysis of the statistics *V*, *MD*, *DPD* is not appropriate due to the fact that they complement the analysis. In this sense, the choice of the best method was assessed according to the classification proposed by the smaller sum of statistics of the variables in each estimation process together with *CV*, *Syx* (%) and graphical analysis of residuals.

RESULTS AND DISCUSSION

Adjustment of Models:

At first, only the coefficients for the situations proposed in methods 1a, 1b, 2a, 2b, 3 and 4 were estimated, as shown below:

Method using the quadratic diameter estimated - Method 1a and 1b:

For the methods 1a and 1b the resulting equations and their statistics are presented in the expressions (32) and (33) and all coefficients were significant at 95% probability.

Method 1a $d_q^2 = 16{,}8597 + 0{,}3705 dap^2$; *Syx* (%)=21.44; R^2=96.57 (32)

Method 1b $d_q^2 = -34{,}6557 + 6{,}4404 dap + 0{,}2040 dap^2$; *Syx* (%)= *19.23; R2*=97.24 (33)

The estimate of the volume, based on the proposed methodology for these methods was performed, obtaining their corresponding statistics for evaluation, presented in Table 2.

Method using the mean quadratic diameter regression in volumetric methods 2a and 2b:

The equations adjusted with their estimated coefficients, all significant at 95% probability by using the t-test, are presented in (34) and (35):

Method 2a $\hat{y} = 0{,}000032\ dap^2$; *Syx* (%)=13.12; R^2=96.57 (34)

Method 2b $\hat{y} = 0{,}00019\ dap_i + 0{,}000023\ dap^2$; *Syx* (%)=*11:23*; R^2=97.50 (35)

The estimate of the volume, based on the proposed methodology for these methods was performed, obtaining their corresponding statistics for evaluation, presented in Table 2.

Method of relative height - Method 3:

The equations adjusted with their respective coefficients are presented in (36) and (37):

$$\hat{\mu}_I = -1.2499 dap_i^{-1.2727} ht_i^{1.4581}\ ;\ s_{yx}(\%) = 12.18; R^2 = 82.19\% \tag{36}$$

$$\hat{\mu}_{II} = -1.8552 dap^{0.8591} ht^{0.8326}\ ;\ s_{yx}(\%) = 6.64; R^2 = 91.11\% \tag{37}$$

These results were replaced in the equations (19) and (20), thereby establishing the following expressions for estimates of diameters along the bole:

$$\mu_I = -1.2499\, dap^{-1.2727} ht^{1.4581} = 2\left[(1.3-h)\,(dap-d_I)^{-1}\right]$$
$$d_I = dap^{-1.2727} ht^{1.4581}(2.0802 - 1.6001\,h) + dap \quad (38)$$
$$-\mu_{II} = -1{,}8552 dap^{0{,}8591} ht^{0{,}8632} = (2ht-2h)^{-1}$$
$$d_{II} = dap^{0.8591} ht^{0.8632}(1.0781\,ht - 1.07801\,h) \quad (39)$$

The volume obtained by this method required the diameters estimated by the expression *dI* from the base up to the *hr*, and with an average of expression *dI* and *dII* for diameters from *hr* to *ht*.

Method using the Schumacher-Hall Model - Method 4:

Using non linear regression method, the coefficients of Schumacher-Hall model for total volume were estimated. All coefficients were significant at 95% probability by the t-test. The adjusted model is presented in (40):

$$V = 0{,}000017\ \ dap^{\,1{,}6559}\ ht^{\,1{,}5181}$$; *Syx* (%)=10.06; R^2=97.98 (40)

Total Volume Estimation:

On the basis of adjustments and rearrangements made, when necessary, the total volumes were estimated by the four methodologies used, and they were compared to the actual volumes calculated by Huber's method. Statistics of obtained accuracy are presented in Table 2, and the residual distributions in Figure 2.

To evaluate the accuracy of volume estimates, statistics *Syx* (%) and *CV* were considered, and also the classification obtained by statistics *V*, *MD* and *DPD*, in addition to the analysis of the residuals. Consequently it was possible to establish the best model to estimate the total volume (Table 2).

Table 2: Statistics *Syx* (%), *CV*, bias *(V)*, mean absolute differences *(MD)*, standard deviation of the differences *(DPD)* and the classification for estimates of total volume.

	Method 1a	Method 1b	Method 2a	Method 2b	Method 3	Method 4
Syx (%)	11.8608	10.8214	13.1231	11.2319	12.7206	10.0612
CV	0.1197	0.1083	0.1353	0.1126	0.1221	0.1009
V	0.0032 (4)	0.0003 (1)	0.0107 (5)	0.0008 (2)	-0,0149 (6)	0.0011 (3)
MD	0.0298 (4)	0.0257 (2)	0.0348 (5)	0.0278 (3)	0.0278 (3)	0.0239 (1)
DPD	0.0020 (4)	0.0017 (2)	0.0023 (6)	0.0018 (3)	0.0021 (5)	0.0014 (1)
Sort.	12	5	16	8	14	5

Obs.: Method 1a - using the quadratic diameter estimated in linear form; Method 1b - using the quadratic diameter estimated in parabolic form; Method 2a - using the quadratic diameter in the volumetric regression as independent variable; Method 2b - using the quadratic diameter and in its linear form in the volumetric regression as independent variables; Method 3 - using relative height; Method 4 - using regression analysis

The values of *Syx* (%) presented a suitable accuracy for all methods (not exceeding 14 %). The method 4 presented values closer to the real ones, with minor errors, generating more accurate estimates when compared to other used methods. The values of *CV* also followed the same trend of the values of *Syx* (%) and, in this case, the Schumacher-Hall model for total volume presented the closest deviations to the average volume. Similar result can be found in the work of Guimaraes (1986), Thomas *et al*. (2006) and Silva *et al*. (2011).

For the statistics *V*, *MD* and *DPD* (Table 2), it is noted that the results have the same characteristics as the graphical analysis of residuals (Figure 2). For the statistic bias, it can be noticed, by graphical analysis of residuals, that the adjustments 1b and 2b, even showing a trend in smaller diameters to overestimate or underestimate the total volume, presented low values on the average, near to those estimated by the Schumacher-Hall model (method 4), traditionally used to estimate the total bole volume in eucalyptus plantations in Brazil. Thaines *et al*. (2010) testing seven volumetric models to estimate the volume of wood of different species in Ituxi River basin, Labrea, AM, have concluded that for felled trees, as those used in this study, the Schumacher-Hall model should be used to estimate biomass and carbon stock.

In this way, we can affirm that the volumes under- or overestimated to *dbh* < 10 cm presented in graphics of residuals have not influenced significantly the average accuracy of the estimated values in relation to the total volume calculated by the Huber method. Already the methods 3 and 2 showed a tendency to estimate the total volume when compared to the Schumacher-Hall model.

The same explanation corroborates with the results for the *MD* and *DPD* statistics, showing that the methods 3 and 2 have presented lower accuracy than that obtained in other studied methods. This can be explained by the fact that the method 3 uses only one diameter measured on boles beyond the *dbh* to estimate the total volume and the method 2a uses the quadratic diameter with only one independent variable, not resulting in a satisfactory average estimate.

Analyzing the sum of the values of the three statistics, the method 4 was the most appropriated and most accurate for the total volume estimate, followed by the model 1b, which uses the regression from the diameter in quadratic form, while method 3 was the least accurate.

Testing several models for estimation of total volume of *Pinus taeda* (Thomas *et al*., 2006) and for native commercial species in Paragominas, PA (Silva *et al*., 2011), they concluded that the Schumacher-Hall model showed the best fit to data and generated the best volume estimates.

As shown in Figure 2, the method 3 presented a better distribution of residuals for the total volume. However, when compared to method 4, which had mild tendency to overestimate volumes of trees with smaller diameters, it is possible to notice that in the method 3 larger errors occur in larger diameter classes; consequently the selection of the method 4 is more appropriated because it gives smaller errors.

Even considering Figure 2, it can be observed that the method 1a and 2b have a strong tendency to overestimate the volume of trees with *dbh* < 10 cm. Also the method 1b underestimates the volume on this situation. Method 2a shows tendency to underestimate the majority of tree volumes until a *dbh* of 20 cm. However, the methods 1b and 2b, even resulting in trends of sub- and overestimation respectively, present errors and classification in the ranking of additional statistics near to the model 4, which may also be indicated for the volume estimation.

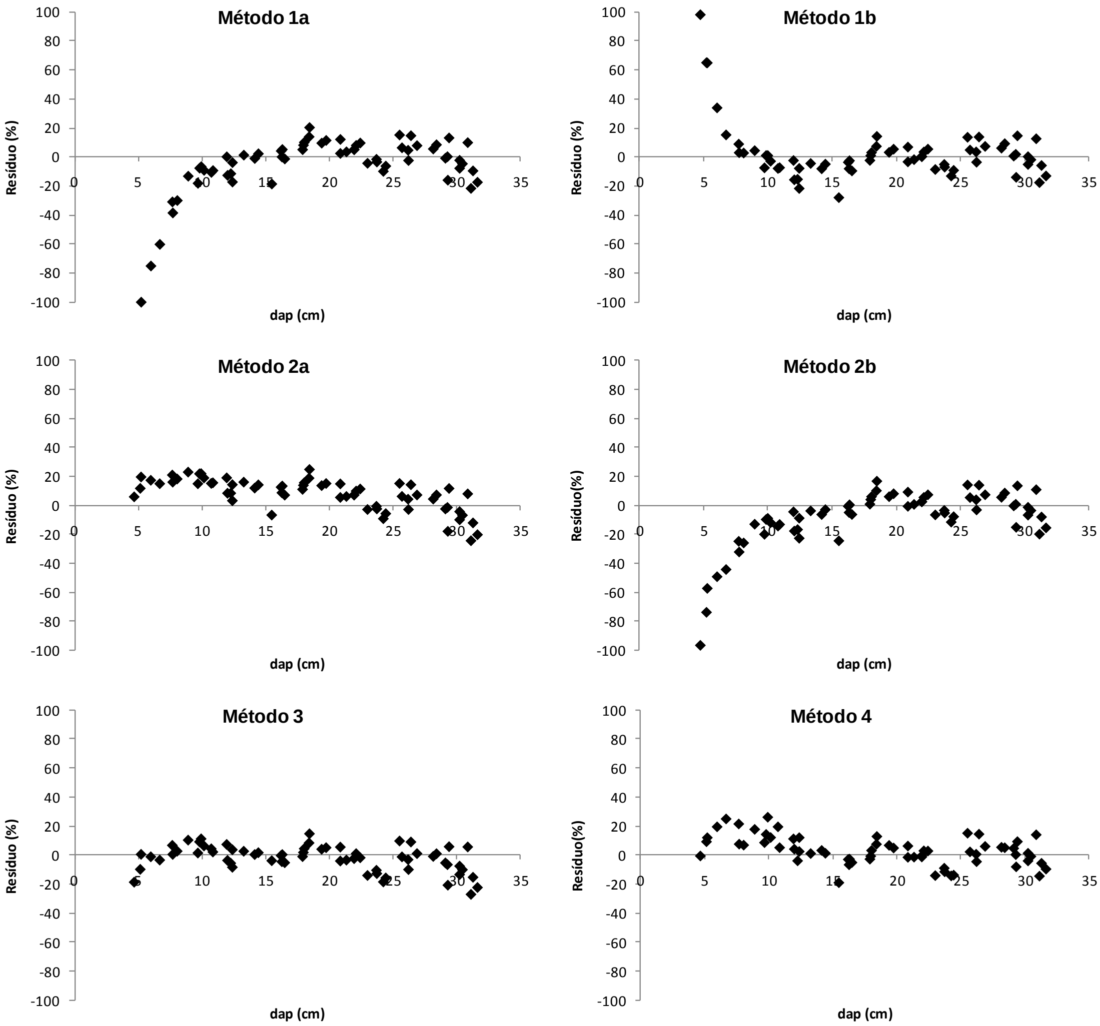

Fig. 2: Distribution of the residuals for the variable volume in percentage, as a function of *dbh*, obtained on the basis of the proposed methodologies.

Conclusion:

According to the results, it can be inferred that the all methods, except the 2a, estimated on the average volumes with good accuracy;

The methods 1b and 2b, using as independent variable quadratic diameter and in its linear form, are also appropriated for volume estimation.

The method 3 should not be used to estimate total volume of trees, because super estimations can occur in larger trees.

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