VOLUME ESTIMATE FOR THREE TIMBER SPECIES WITH COMMERCIAL INTEREST FROM THE DIAMETER OF THE STUMP

Quelyson Souza de Lima[1]*, Thiago Augusto da Cunha[2], Marco Antonio Amaro[3], Evandro Orfanó Figueiredo[4] Paulo Roberto Feitosa Parente[5]

[1]*Instituto de Meio Ambiente do Acre, Divisão de Manejo Florestal, Rio Branco, Acre – quelyson.lima@gmail.com
[2]Universidade Federal do Acre, Centro de Ciências Biológicas e da Natureza, Rio Branco, Acre – etsfor@yahoo.com
[3]Universidade Federal do Acre, Centro de Ciências Biológicas e da Natureza, Rio Branco, Acre – marcoantonioamaro@gmail.com
[4]Empresa Brasiliera de Pesquisa Agropecuária, Rio Branco, Acre – evandro.figueiredo@embrapa.br
[5]Complexo Industrial Florestal Xapuri S.A., Xapuri, Acre – paulorfparente@hotmail.com

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Resumo

Estimativa do volume para três espécies de interesse comercial madeireiras a partir do diâmetro do toco. O volume comercial de árvores pode ser calculado de forma direta e indireta. Entretanto em áreas de desmatamento ilegal, muitas vezes o fuste não está disponível para medições dendrometricas e, consequentemente, cálculo do volume comercial, e a utilização do método direto. Por outro lado, o uso do método indireto é impossível devido a não existência de equações com variáveis de possível medição. Para viabilizar a estimativa de volume nestes casos, o objetivo desse trabalho foi estimar o volume comercial de madeira de árvores individuais através de equações de regressão, utilizando medições realizadas no toco para três espécies de interesse comercial, em áreas de manejo florestal madeireiro, sendo elas: *Dipteryx odorata* (Aubl.) Willd., *Apuleia leiocarp*a (Vogel) J.F.Macbr. e *Amburana acreana* (Ducke) A.C.Sm.. Os dados foram coletados em duas áreas de manejo, localizadas nos municípios de Sena Madureira e Rio Branco, com amostra de 250 tocos. Foram realizados testes estatísticos para análise de regressão e escolha das melhores equações que estimassem o volume das espécies selecionadas para o estudo, à partir do diâmetro do toco. Testes de exatidão, precisão, pressupostos, validação e modelo identidade foram aplicados para escolha. Foram testados modelos que atenderam os objetivos da pesquisa para ambas as espécies com R^2_{ajus} = 87,7% para *Dipteryx odorata* (Aubl.) Willd., R^2_{ajus} = 81,8% para *Apuleia leiocarp*a (Vogel) J.F.Macbr. e R^2_{ajus} = 70,5% para *Amburana acreana* (Ducke) A.C.Sm., assim como atenderam todos os pressupostos da regressão tendo como resultado a validação das equações ajustadas pelos modelos selecionados.
Palavras-chave: Floresta Amazônica; alometria; fiscalização ambiental.

Abstract

The commercial volume of trees can be calculated directly and indirectly. However, in areas of illegal deforestation, the stem is often not available for dendrometric measurements and, consequently, calculation of the commercial volume and the use of the direct method. On the other hand, the use of the indirect method is impossible due to the lack of equations with possible measurement variables. In order to make the volume estimate feasible in these cases, the objective of this work was to estimate the commercial volume of wood from individual trees using regression equations, using measurements made on the stump for three species of commercial interest, in areas of timber forest management, namely: *Dipteryx odorata* (Aubl.) Willd., *Apuleia leiocarpa* (Vogel) JFMacbr. and *Amburana acreana* (Ducke) A.C.Sm. Data were collected in two management areas, located in the municipalities of Sena Madureira and Rio Branco, with a sample of 250 stumps. Statistical tests were carried out to analyze regression and choose the best equations that would estimate the volume of the species selected for the study, based on the diameter of the stump. Tests of accuracy, precision, assumptions, validation and identity model were applied for choice. Models that met the research objectives for both species were tested with R^2adj = 87.7% for *Dipteryx odorata* (Aubl.) Willd., R^2adj = 81.8% for *Apuleia leiocarpa* (Vogel) J.F.Macbr. and R^2adj = 70.5% for *Amburana acreana* (Ducke) A.C.Sm., as well as meeting all the assumptions of the regression resulting in the validation of the equations adjusted by the selected models.
Keywords: Amazon rainforest; allometry; environmental inspection.

INTRODUCTION

Illegal logging still occurs in the Amazon rainforest and has been developing in extensive areas of vegetation cover, causing immeasurable losses of genetic resources, where rare species have been decimated and several habitats have been modified by anthropic actions, affecting the resistance and resilience of ecosystems (SILVA *et al*., 2015). Combined with occupation and deforestation, this activity results in a real threat to the protection of biodiversity in the Legal Amazon (LEMOS; SILVA, 2011), provided deforestation is a catalyst for forest fragmentation resulting in changes in carbon stocks (BARROS; FEARNSIDE, 2016).

One of the attempts to reduce illegal logging in the Amazon was Provisional Measure 1511/96, which increased the Legal Reserve from 50% to 80% (ALMEIDA *et al*., 2013). However, other alternatives have been developed over time in order to adjust policy and resource allocation in the face of current forest destruction (GODAR *et al*., 2012).

According to Amin *et al.* (2019), the creation of conservation units can also be a strategy for reducing deforestation rates in the Brazilian Amazon, since extensive areas are created aimed at the protection and/or sustainable use of resources.

In the case of inspection in areas of illegal logging, obtaining the commercial volume in an accurate manner is of relevant importance for the better legal framing of the Notices of Infractions according to Federal Decree No. 6514/2008, which is the administrative legal basis used for legal framing of the infraction.

Therefore, calculating the volume of timber harvested in areas of illegal deforestation during environmental inspection actions is difficult given the situation that in many cases only the stump remains as part of the tree, which makes it impossible to adopt classic methods for calculating the volume from diameter measurements along the stem.

Some authors estimate the commercial volume of trees based on measures of the diameter of the stump as an input variable in a regression equation (GIMENEZ *et al.*, 2015); (LEITE; REZENDE, 2010). Other authors used stump measurements, namely height and diameter, to obtain the diameter at breast height estimate in order to estimate the volume of a population (PONDE; FROESE, 2014); (WESTFAL, 2010).

However, the accuracy of estimates for volume from regression equations deserves to be evaluated in view of the great diversity of forms of timber species in the Amazon. In this way, this research evaluated the performance of the estimation of regression equations to calculate the commercial volume of trees harvested illegally, using measures of the remaining stump in the forest. The species evaluated correspond the main trees currently exploited in the state of Acre: *Dipteryx odorata* (cumaru-ferro), *Apuleia leiocarpa* (garapeira) and *Amburana acreana* (cerejeira) (SILVA *et al.*, 2015).

MATERIAL AND METHODS

The trees used for this study were sampled within two Annual Production Units (APU) in a forest management regime located in the municipalities of Rio Branco and Bujarí in the state of Acre (Eldorado Farm UTM X 643083,400 and Y 8886079,195 and Antimary State Forest (X 606238,686 X and Y 8968718,409 Y) as shown in Figure 1.

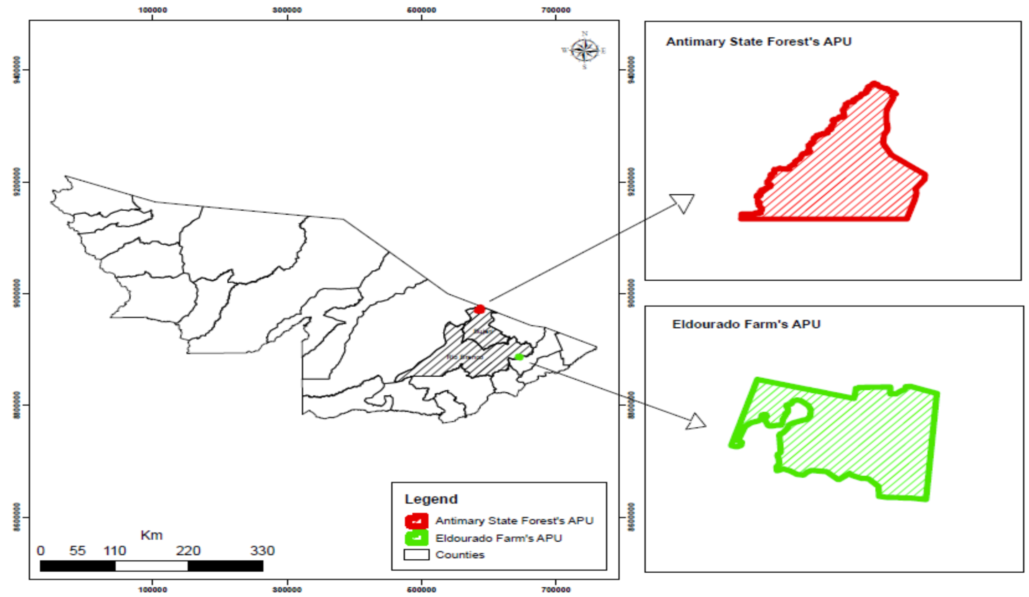

Figure 1. Map of the location of study areas in the State of Acre.
Figura 1. Mapa de localização das áreas de estudo no Estado do Acre.

This state has an average rainfall of 1944 mm per year (range 1566–2425 mm per year) with a rainy period occurring between October to April and the dry season between June to August, with the months of May and September comprising the dry season, when rainfall reaches levels below 50 mm (DUARTE, 2006).

The vegetation of the Eldourado Farm is predominantly classified as Open Forest with Palm Trees, while the Antimary State Forest has vegetation of the type Open Forest with Palm and Open Forest with Bamboo. The predominant type of landscape in the study areas is the gently undulating plain, and the dominant soils that occur

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in the areas covered by the municipalities, where the areas of the properties are located, belong to the Argisols and Latosols Classes.

Species evaluated and strategy for data collection and modeling

The selected individuals are in a group with the highest rates of exploitation in the state of Acre, being the species *Dipteryx odorata* (Aubl.) Willd. (cumaru-ferro), *Apuleia leiocarpa* (Vogel) J.F.Macbr. (garapeira) and *Amburana acreana* (Ducke) A.C.Sm. (cherry tree). These species are also the main forest essences licensed in the state of Acre (SILVA *et al.*, 2015).

To measure the botanical recognition, exsiccates collected in the field were used, which were compared with exsiccates deposited in the herbarium of the Federal University of Acre (UFAC).

Of the total number of trees legally felled within the APU by forestry activities, 250 individuals were randomly selected, distributed among the three species and stratified into six classes of DBH, with the amplitude of class 10 cm, the lowest DBH 50 cm and the largest greater than 100 cm. The frequency of the lowest class was 5 and greater than 26 individuals.

To locate the felled trees, GPS navigation Garmim 76 CSX with UTM coordinates, DATUM SIRGAS 2000 was used with the aid of the exploration map.

On each localized stem, the dimensions of diameter and length were measured for applying Smalian's formula for each section. The volme of each section were summed to reconstruct the stem and obtain the total commercial volume for each individual.

The average diameter of the respectively stump also were calculated . The measures was obtained from two directions with 90° angles for shapes tending to cylindrical. In the case of presence of buttress, the average diameter was calculated from several measurements of diameters considering all extremities (buttress), and the geometric mean was calculated according to the methodology proposed by Gimenez *et al.* (2015).

To mathematically describe the observed data of commercial volume of logs we used the average diameter of the stump as a predictor by fitting five regression models (Table 1).

The decision to use the regression models was based on the behavior of the data observed in dispersion diagram graphs considering the commercial volume as a function of the average diameter of the stump based on the biological behavior (VANCLAY; SKOVSGAARD, 1997).

Table 1. Models tested for the adjustment of the volumetric equations as a function of the diameter of the stump.
Tabela 1. Modelos testados para o ajuste de regressão para equação volumétrica em função do diâmetro do toco.

Number	Model	Authors
1	$Ln\, V_c = \beta_0 + \beta_1 LnD_t + \varepsilon$	Husch
2	$LnV_c = \beta_0 + \beta_1 LnD_t + \beta_2 D_t^{-1}$	Brenac
3	$V_c = \beta_0 + \beta_1 D_t^2 + \varepsilon$	Kopezky-Gehrhrdt
4	$V_c = \beta_0 + \beta_1 D_t + \varepsilon$	Berkhout
5	$V_c = \beta_0 + \beta_1 D_t + \beta_2 D_t^2 + \varepsilon$	Hohenald & Krenn

Where: V_c = commercial volume; D_t = stump diameter β = regression coefficient; ε = residue.

Initial analysis

In order to indicate the analyses, it is necessary to know the behavior between the variables, so it was necessary to build a dispersion graph and an analysis of Pearson's Correlation (r) (CUNHA *et al.*, 2016). In addition, the behavior of the data studied was observed, including their minimum, maximum and average values, since they can assist in making technical decisions due to the similarities of the measured and morphological variables.

Selection criteria for the best equation

In the statistical analysis performed on the SAS System V8, a probability of $\alpha = 0.05$ was considered, as recommended by Cunha *et al.* (2016).

To choose the best regression equation for volume estimation, accuracy statistics were used according to Figueiredo *et al.* (2014); Amaro *et al.* (2013): Value F, Adjusted Coefficient of Determination ($R^2adj\%$), Standard Error of the Estimate ($Syx\ m^3$) and Coefficient of Variation (CV%).

FI was used to compare regression equations with different units for the dependent variable, as reported by Viana *et al.* (2013).

In order to control the effects of collinearity in multiple regression models, as proposed by Ribeiro *et al.* (2014), the Variance Inflation Factor (VIF) was calculated. Thus, only the equations remained in which all the independent variables showed VIF values less than 5 (CUNHA *et al.*, 2016).

Equations with VIF greater than 5 and non-significant regression coefficients in at least one regression variable were excluded.

The Pondered Value (PV) was applied to select the best one according to the scores of each equation (SOUSA *et al.*, 2013).

For the best selected regression equation, assumptions of regression tests were carried out according to Ribeiro *et al.* (2014); Schröder *et al.* (2013), for normality (Shapiro–Wilk test), homogeneity of variance (White test) and independence of residues (Durbin–Watson test).

Finally, the graphic distribution of the residues was verified to observe the behavior of the data for the selected equation, since according to Amaro *et al.* (2013) residues are important elements to visualize the performance of the regression equation.

Equation validation

For the validation of the best adjusted equation, the Chi-square test was used according to the methodology proposed by Ribeiro *et al.* (2014), by collecting a new sample of 15 pairs of data per species (volume and diameter of the stump). As recommended by Leal *et al.* (2015), the collection was carried out in an area of forest different from the main sample.

This methodology aims to evaluate the effectiveness of the estimates in the face of different situations in which the trees are.

Model identity

To assess the adequacy of a single regression equation for the three species, each equation passed the identity test, determined by the covariance analysis which assessed the influence of a common intercept (species) and the interaction (species × LnDt) for the purpose of an angular coefficient, with a probability test on different values of diameter of the stump.

After the selection and verification of the tests for choosing the model, the possibility of grouping the species to fit a single equation was verified through the test (CYSNEIROS *et al.*, 2017).

For all statistical analyses, the SAS System version SAS University was used, considering the PROC REG procedures for regression analysis, PROC CORR for correlation analysis, PROC MODEL for the analysis of regression assumptions and PROC GLIMMIX for the analysis of covariance.

All statistical analyses were performed using the SAS System V8 with an alpha significance level of 0.05 (CUNHA *et al.*, 2016).

RESULTS

Pearson's Linear Correlation results showed a positive association between the variables for the three species, with *Dipteryx odorata* r = 0.93, *Apuleia leiocarpa* r = 0.90 and *Amburana acreana* r = 0.83.

It is important to highlight that *Amburana acreana* was the species that showed the lowest correlation between the variables, even with a strong association. The lowest correlation value occurred for *Amburana acreana* since the dispersion of the data pairs showed a slight slope in the dispersion, different from the other species that present a more accentuated linear trend (Figure 2).

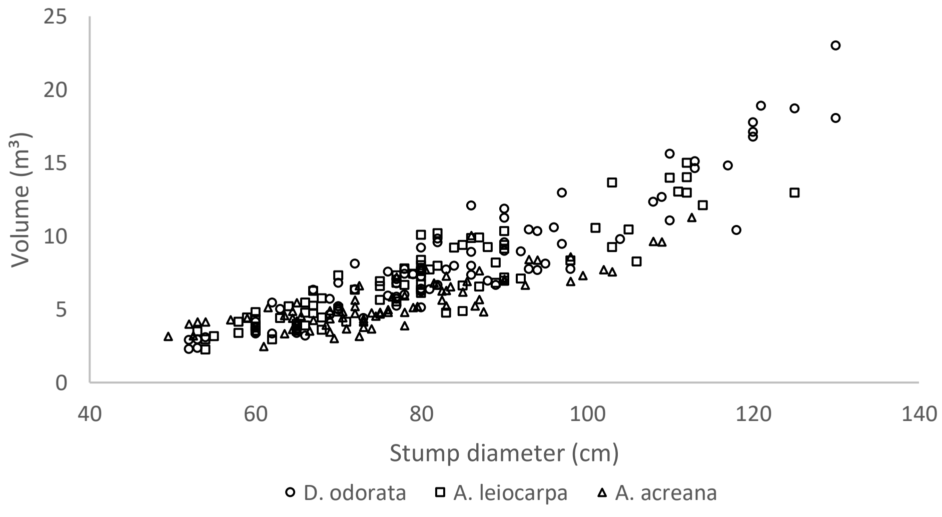


Figure 2. Pearson's correlation graph for the volume and diameter of the stump.
Figura 2. Gráfico de correlação de Pearson para volume e diâmetro do toco.

For the average of the diameters, we can observe that the species *D. odorata* obtained the highest result for this statistical variable, being an average of 84.7 cm, followed by *A. leiocarpa* with 79.38 cm and *A. acreana* with 76.33 cm. This is due to the fact that the first two species have a greater number of individuals larger than the third (Table 2).

Regarding the average value of the cubed volume and the estimated average volume obtained through the equation, a small variation was observed between them, with *A. acreana* 0.00001 m³, *A. leiocarpa* 0.09438 m³ and *D. odorata* 0.10687 m³ (Table 2).

It can also be observed that the smallest variation between the observed and estimated volumes adjusted through the selected equation was for the species *A. acreana* with variation of 0.00001 m³, *A. leiocarpa* with 0.09438 m³ and *D. odorata* with 0.10687 m³ (Table 2).

Table 2. Observed of values of attributes of the three species evaluated.
Tabela 2. Valores observados de atributos das três espécies avaliadas

Species	Variables	Stump diameter (cm)	Cubing volume (m³)	Volume of equations (m³)
Dipteryx odorata (n=85)	Minimum	52	2,30392	2,77664
	Maximum	130	23,01091	19,3938
	Medium	84,7	8,402550	8,29568
Apuleia leiocarpa (n=82)	Minimum	53	2,25211	3,10085
	Maximum	125	15,01581	15,91175
	Medium	79,38	7,036870	6,94249
Amburana acreana (n=83)	Minimum	50	2,48570	2,97043
	Maximum	112,6	11,27310	10,13069
	Medium	76,33	5,45935	5,459360

The equations generated by the processing of the regression models tested are shown in Table 3, where the species, model and the resulting equation of the adjustment are presented.

Table 3. Equations adjusted by the models for the evaluated species.
Tabela 3. Equações ajustadas pelos modelos para as espécies avaliadas

Species	Model	Equation
Dipteryx odorata	1	$LnV = - 7,36045 + 2,12128 \times LnDt$
	2	$LnV = -9,03143 + 2,61062 \times LnDt + 0,00577 \times 1/Dt$
	3	$V = - 0,37752 + 0,00116 \times Dt^2$
	4	$V = - 0,2702 + 0,20864 \times Dt$
	5	$V = 1,03921 - 0,03266 \times Dt + 0,00134 \times Dt^2$
Apuleia leiocarpa	1	$LnV = -6,43566 + 1,90599 \times LnDt$
	2	$LnV = -10,71269 + 3,17590 \times LnDt – 0,01577 \times 1/Dt$
	3	$V = 0,73398 + 0,00095936 \times Dt^2$
	4	$V = - 5,96631 + 0,16381 \times Dt$
	5	$V = -5,37752 + 0,14925 \times Dt + 0,00008635 \times Dt^2$
Amburana acreana	1	$LnV = -4,54407 + 1,43334 \times LnDt$
	2	$LnV = 3,91565 -1,11588 \times LnDt + 0,03344 \times 1/Dt$
	3	$V = 1,25518 + 0,00070003 \times Dt^2$
	4	$V = - 2,96777 + 0,11041 \times Dt$
	5	$V = 4,13679 – 0,07375 \times Dt + 0,00116 \times Dt^2$

Where: LnV = Natural volume logarithm; V = volume (m^3); LnDt = Natural logarithm of the stump diameter; Dt = Stump diameter (cm).

For the species *Dipteryx odorata* and *Apuleia leiocarpa*, the equations resulting from models 2, 3 and 5 were excluded since for *Dipteryx odorata* the equations adjusted by model 2, the regression coefficients β0 and β1 had VIF equal to 54.76 in addition to presenting β2 not significant. In the case of model 3, its exclusion was due to the fact that the regression coefficient β0 is not significant, whereas in the equation generated by model 5, β0 and β1 were not significant, with β1 also presenting higher VIF than adopted in the methodology, as well as β2 with VIF equal to 63.96.

In the case of *Apuleia leiocarpa*, model 2 was excluded for the same reason as the previous species, differentiating only the value of the VIF, which was 72.58. Model 3 showed β0 not significant, whereas in the equation generated by model 5, β0 and β1 were not significant, with β1 also presenting higher VIF than the methodology, as well as β2 with equal VIF 74.67.

However, unlike the species previous to *Amburana acreana*, the models resulting from the application of VIF and the significance of the regression coefficients were 1, 3 and 4, emphasizing that the exclusion of model 2 was due to the values of β0 and β1 being not significant, in addition to β1 and β2 having a VIF equal to 71.24, and the same goes for the equation adjusted by model 5 with respect to the significance of the coefficients β0 and β1, emphasizing that the VIF for β1 and β2 was equal to 76.50. After filtering, the criteria for selecting the best model for the resulting equations were applied (Table 4).

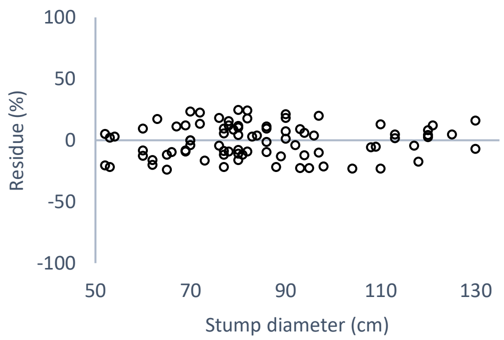
Table 4 Adjusted equations and accuracy statistics with ranking by species.
Tabela 4. Equações ajustadas resultantes e estatísticas de acurácia com ra*nking* por espécie.

Species	**Equation**	**R^2adj (%)**	**Syx (m^3)**	**CV%**	**F**	**Model**	**Ranking**
Dipteryx odorata	LnV=-7,36045+2,12128xLnDt	87,7	±1,26*	14,99*	609,02	1	1º
	V=-9,2702+0,20864xDt	86,0	±1,62	19,31	516,91	4	2º
Apuleia leiocarpa	LnV=-6,43566+1,90599xLnDt	81,8	±1,16*	16,47*	358,57	1	1º
	V=-5,96631+0,20864xDt	81,2	±1,30	18,57	350,41	4	2º
Amburana acreana	$V=1,25518+0,00070003xDt^2$	70,5	±0,97	17,87	197,29	4	1º
	LnV=-4,54407+1,43334xLnDt	64,1	±0,93*	17,13*	147,03	1	2º
	V=-2,96777+0,11041xDt	68,4	±1,01	18,51	178,29	3	3º

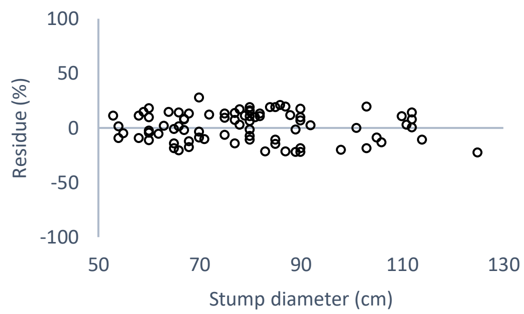
Where: LnV = Natural volume logarithm; V = volume (m^3); LnDt = Natural logarithm of the stump diameter; Dt = Stump diameter (cm); * correction by FI.

According to Table 4, model 1 was the one that best fit the data of commercial volume and stump diameter for the species *Dipteryx odorata* and *Apuleia leiocarpa*, and model 4 (Hohenald & Krenn model) was the best fit for *Amburana acreana*, both of which are simple input equations.

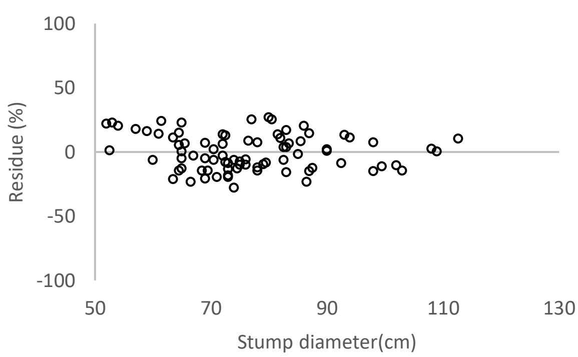
The following is the graph of dispersion of residues of the species studied (Figure 3).



(a) *Dipteryx odorata*



(b) *Apuleia leiocarpa*



(c) *Amburana acreana*

Figure 3. Residual distribution by species.

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Figura 3. Gráfico de distribuição dos resíduos por espécie

The Chi-square probability test revealed adequacy of the estimates for the test sample for all species (*Dipteryx odorata* with a value of 0.9982, *Apuleia leiocarpa* with a value of 0.9999 and *Amburana acreana* with a value of 0.9987).

The model identity test showed that the *Dipteryx odorata* and *Apuleia leiocarpa* species commercial volume can be estimated by a single regression equation according to covariance in the common intercept (species, $Pr > 0.05$) and in the interaction (species × LnDt , $Pr > 0.05$) as assessed in the lines of Figure 4.

In the case of *Amburana acreana*, there was a common intercept. However, for trees with a stump diameter greater than or equal to 66.00 cm, there is a change in the slope as the probability test presented ($Pr < 0.05$).

Therefore, the equation resulting from the Husch model was $LnV = -6.63018 + 1.9114 \times LnDt$, with R^2adj (%) = 85.36, Syx = ± 1.13, CV (%) = 16.22 and F = 963.01, for identity between models.

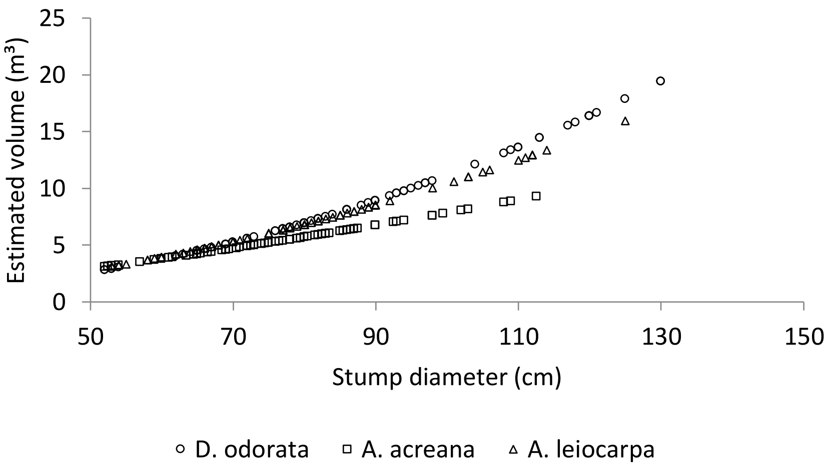

Figure 4. Volume estimated by equation adjusted for the three species by the Husch model.
Figura 4. Volume estimado por equação ajustada para as três espécies pelo modelo de Husch.

DISCUSSION

The use of variables with a strong correlation indicates the possibility of good equation adjustments. When the results of the analysis for the correlation between the studied variables were observed, a strong positive correlation was observed between them, with a value equal to or greater than 90% for the species *Apuleia leiocarpa* and *Dipteryx odorata*, these results being similar to those presented by Cunha *et al.* (2016). For *Amburana acreana*, the value was lower than that found for other species. However, as observed by Bett; May (2017), is a good result.

The best fit was obtained by the Husch model, for the species *Dipteryx odorata* and *Apuleia leiocarpa*, in the present study. Leite and Resende (2010) carried out a study for a population with several species, obtaining better results for the Berkhout model to estimate the volume from the diameter of the stump.

In the case of *Amburana acreana*, the model that provided the best fit was the Kopezky-Gehrhardt model (Table 4), with a lower coefficient of determination than that obtained for the other species studied. Despite this, Leite *et al.* (2003) consider that values above 60% for the determination coefficient present values of goodness of fit for species in Amazon.

Miranda *et al.* (2013) and Gimenez *et al.* (2015) carried out studies using double entry equations with DBH and CH (commercial height) variables for the population and, excluding the coefficient of determination, obtained statistics similar to those obtained by the present study.

Regarding the tests of the regression assumptions, just as in the study by Cunha *et al.* (2016), the equations adjusted by the models selected for the three species met the same, presenting homogeneity, independence and normality of the residues.

The behavior of the percentage residues for the equations selected for the species *Dipteryx odorata*, *Apuleia leiocarpa* and *Amburana acreana* in the present study revealed the absence of a trend along the distribution, as in the studies by Amaro *et al.* (2013); Milk; Resende (2010).

With the application of the Chi-square test, in which the values of the calculated volume and volume estimated by the regression were compared, it was observed that there was no statistical difference between them,

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just as other authors used the test to validate the data, which can be mentioned among them Leal *et al.* (2015); Barros; Silva Júnior (2011).

The model identity study assumes the use of a single model. Although Husch's model was not the best for *Amburana acreana*, it was used in the model identity for the three species. With the stump diameters approaching the 60 cm class, the model for *Amburana acreana* follows an angular distribution trend different from *Dpteryx odorata* and *Apuleia leiocarpa*, thus demonstrating that there is a variation that does not allow the use of a single equation for the three species.

CONCLUSIONS

- It was possible to estimate the volume using statistical equations precisely using the diameter of the stump.
- Volume equations for the species *Dipteryx odorata*, *Amburana acreana* and *Apuleia leiocarpa* were adjusted, with the Husch model showing the best fit resulting in the equations $LnV = -7.36045 + 2.12128 \times LnDt$ and $LnV = -6.43566 + 1.90599 \times LnDt$, respectively, and for *Amburana acreana* the best model was Kopezky-Gehrhardt resulting in the equation $V = 1.255518 + 0.00070003 \times Dt^2$.
- All the selected equations met the tests of regression assumptions (normality, independence and homogeneity) for the residuals.
- The Chi-square test demonstrated the validity of the equations, since there were no statistical differences when comparing the estimate result with the volume obtained through the rigorous cubing of the sampled individuals.
- It was not possible to obtain a single equation for the studied species, since with Dt equal to or greater than 66.60 cm, the regression slopes show different behavior.

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