MIXED-EFFECT MODELS FOR VOLUMETRIC ESTIMATION OF LUMBER FROM NATIVE AMAZONIAN SPECIES

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Resumo

Modelos de efeito misto para estimativa volumétrica de madeira serrada de espécies nativas da Amazônia. O objetivo do presente trabalho foi testar modelos de efeito fixo e comparar com diferentes configurações de modelos mistos, para predicação volumétrica de madeira serrada de espécies comerciais da floresta amazônica. A base de dados foi proveniente de uma serraria de médio porte, localizada na zona rural do município de Porto Grande, Amapá. Foram utilizadas 50 toras de 9 espécies nativas as quais foram cubadas rigorosamente, pelo método de Smalian. Foi ajustado um modelo de efeito fixo proposto por Lima *et al.* (2018), em comparação com os modelos lineares mistos, com as espécies como efeito aleatório. O ajuste do modelo fixo e dos modelos mistos foram realizados adotando-se o método de máxima verossimilhança. Para seleção do melhor modelo foram utilizados os critérios de informação de Akaike (AIC), Teste da Razão de Máxima Verossimilhança e Raiz Quadrada do Erro Médio (RMSE) e análise gráfica dos resíduos. Segundo os critérios estabelecidos, os modelos mistos obtiveram melhores ajustes quando comparados com o modelo fixo, proporcionando uma redução na raiz quadrada do erro médio de 0,3 para uma média entre os modelos mistos de 0,26. De acordo com os resultados alcançados, os modelos mistos lineares apresentaram-se mais eficientes e precisos para estimativa de volume. O modelo misto M7 foi o melhor modelo ajustado. O emprego de modelos mistos permite uma maior acurácia na estimativa de volume, visto que com ele foi possível corrigir a heterogeneidade do resíduo.

Palavras-chave: Efeitos aleatórios; modelos de predição de volume, espécies nativas.

Abstract

The objective of the present work is to test fixed effect models and compare them with different configurations of mixed models to predict lumber volume. The database came from a medium-sized sawmill located in the rural area of the municipality of Porto Grande, Amapá, Brazil. A total of 50 logs of 9 native species were used, with their volume being measured by the Smalian method. A fixed effect model proposed by Lima *et al.* (2018) was fitted andcompared to mixed linear models with species as a random effect. The fitting of the fixed model and the mixed models were performed using the maximum restricted likelihood method. Akaike information criteria (AIC), correlation coefficient, Maximum Likelihood Ratio Test, Square Root of the Mean Square Error (RMSE), absolute mean distance and bias were used to select the best model. According to the established criteria, the mixed models obtained better fits when compared to the fixed model, providing a reduction in the RMSE of 0.3 for an average between the mixed models of 0.26. According to the results achieved, the mixed linear models were more efficient and accurate for volume estimation. The M7 mixed model was the best fit model. The use of mixed models enables greater accuracy in estimating volume.

Keywords: Comparison between models, Random effects, Volume prediction models.

INTRODUCTION

Brazil is among the three largest wood producers, behind only Indonesia and India, with production estimated at 29.2 million m³ between 2017 and 2018 (ITTO, 2018). Brazilian native forests produced 12 million m³ of Roundwood in 2019, 62% of which was supplied by the North, the largest producer of tropical native wood (IBGE, 2019). The State of Amapá occupied the 4th position in the volumetric wood production ranking in native logs of the Brazilian states in 2019, and contributed 882,217 m³, which represents 7.3% of the national production (IBGE, 2019). One of the ways of processing this raw material is to convert it into sawn wood, and anticipating the volume of this product by logs makes it possible to estimate its yield (ROCHA, 2002). Knowing this variable in advance of the breakdown is essential for both planning the production process in sawmills (ANJOS; FONTE, 2017), as well as meeting the requirements of environmental agencies (BRASIL, 2018).

The search for tools in the forestry sector which provide prognosis quickly and reliably has driven the use of statistical modeling. Traditional regression models are the most common, however, they do not assume the possible variation of parameters between different hierarchical groups, meaning they only consider the variables which are observable in the environment, called fixed effects (DE-MIGUEL *et al.*, 2013). They lead to estimation errors because they are commonly applied to a set of data from heterogeneous environments, but which can be minimized by using mixed effect models (ABREU *et al.*, 2020a).

When fitting mixed models, it is possible to include the parameters of random effects (which correspond to unobservable characteristics) together with fixed effects, meaning that they incorporate the specific factors of each tree or region in their structure (CARVALHO *et al.*, 2014). Although it is a relatively new approach to tropical forestry, it is an alternative to model correlated data and non-constant variance, constituting conditions which violate the basic assumptions required by regression analysis (GOUVEIA *et al.*, 2015; RUSLANDI *et al.*, 2017).

Examples of applications with precision gain in the use of mixed modeling include making biomass predictions for Caatinga species (ABREU *et al.*, 2020a), estimating total height of *Eucalyptus* sp. (MENDONÇA *et al.*, 2015), and predicting wood volume (ABREU *et al*, 2020b). Monteiro *et al.* (2021) report the use of mixed models to estimate the volume of individual trees in different forest typologies. However, this type of work is non-existent for sawn wood, which justifies the use of the mixed model, because then it will be possible to estimate the volume of sawn wood with more precision.

Assuming the hypothesis that the mixed model will perform better for native forest data, the aim of the present study was to test a fixed effect regression model and to compare it with different configurations of mixed models to estimate lumber production by volume of nine commercial species in the municipality of Porto Grande, AP, Brazil.

MATERIAL AND METHODS

Study area

The data used in the study came from a medium-sized sawmill which processes up to 20,000 m³ of roundwood per year. The sawmill is located in the rural area of the municipality of Porto Grande, Amapá, Amazonia, Brazil (00 ° 41 '53.91" N and 51 ° 26' 4.27" W), approximately 130 km from Macapá, AP, Brazil. Access is via the North Perimeter Highway km 02.

The volumetric production of logs and sawn timber of 9 commercial species was evaluated, which in addition to being established by the consumer market as the most worked, are those which presented processing of more than 50 logs during the analyzed period. These species also come from the farms authorized in the annual operation plans and have good economic return for the company, namely: *Dinizia excelsa* Ducke (Angelim vermelho), *Dipteryx odorata* L. (Cumarú), *Manilkara huberi* L. (Massaranduba), *Carapa guianensis* Aubl. (Andiroba), *Hymenolobium petraeum* Ducke (Angelim pedra), *Goupia glabra* Aubl. (Cupiúba), *Hymenaea courbaril* L. (Jatobá), *Ocotea rubra* Mez (Louro vermelho) and *Vochysia guianensis* Aubl. (Quaruba tinga).

Database

Wood volume in logs

For each species, 50 logs with an average diameter greater than 50 cm were randomly selected. Next, the diameters of the base and the top with bark were measured in each log, in addition to the total length and the volume being estimated by means of rigorous cubing. Hollow measurements were also performed, measuring the diameters that the dimensions occupied in the log in a cross. Only one measurement was performed in logs which did not present distortions in length. The volume was calculated individually by the geometric Smalian method.

Lumber volume

The roundwood of each species was transformed using tangential splitting in a vertical band saw, generating products of different shapes and dimensions according to the commercial demand of the sawmill. Although IBAMA (2016) standardizes parts and products in defined dimensions, the log splitting generated products mostly defined as slats (with dimensions ranging from 0.01 to 0.040 cm thick), rafters (0.2 to 0.40 cm wide) and boards and battens with widths and thicknesses greater than 4 cm. The total length of each product did not exceed 10 m according to the sectioning definition in the log list.

The thickness (T) measurements at each end were obtained using a caliper. The width (W) at each end of the product and the length (L) were measured with a measuring tape. The volume of each product was determined according to Equation 2:

$$Vp = TWL \tag{2}$$

After determining the volumes of the products, they were summed up to obtain the lumber volume for each processed log.

Statistical modeling

A total of 16 models were initially tested for the entire data set based on Lima *et al.* (2018), considering the structure of fixed models. Thus, the fixed model below was fitted with the data for lumber volume, average log diameter and total log volume:

$$lnVls_i = \beta_0 + \beta_1 Lnd_i + \beta_2 LnV_i + \varepsilon_i \quad (3)$$

In which: Ln = Neperian logarithm; Vls = volume of sawn wood, in m³; d = average diameter of the log, in cm; V = volume of log, in m³; β_0 to β_2 = model parameters; ε = random error.

In this study, the variances of the independent variable variances were considered to be homogeneous, since the logarithmic transformation of the data normally provides compliance with this assumption of the classic linear regression model, and the covariances equal to zero, given the non-use of longitudinal data (GUJARATI; POTTER, 2011).

The model fitting was performed using the maximum restricted likelihood method with the *glm2 package* of the R software program. The correction factor for the logarithmic discrepancy was calculated in order to calculate the precision statistics with the lumber values in the original scale due to the transformation of the independent variable. The equation fit in the fixed form was evaluated using the adjusted coefficient of determination, correlation coefficient ($r_{y\hat{y}}$) between observed and estimated lumber volume, square root of the mean square error (RMSE%), bias, mean of absolute differences (MDA) and graphical residual analysis (BINOTI *et al.*, 2015; ABREU *et al.*, 2017).

The fixed model was subsequently fitted considering the structure of a mixed linear model by including random intercepts and slope coefficients, considering the species with a random effect, resulting in the following models (Table 1).

The species was considered as a random effect due to the fact that they have different logs with different log volume and sawn wood volume dimensions, therefore a totally heterogeneous structure which can be used using mixed models.

Table 1. Mixed models tested.
Tabela 1. Modelos mistos testados

Model	Functional form
M2	$LnVls_i = (\beta_0 + a_i) + (\beta_1 + b_{1i})Lnd_i + (\beta_2 + b_{2i})LnV_i + \varepsilon_i$
M3	$LnVls_i = (\beta_0 + a_i) + (\beta_1 + b_{1i})Lnd_i + \beta_2 LnV_i + \varepsilon_i$
M4	$LnVls_i = (\beta_0 + a_i) + \beta_1 Lnd_i + \beta_2 LnV_i + \varepsilon_i$
M5	$LnVls_i = \beta_0 + \beta_1 Lnd_i + (\beta_2 + b_{2i})LnV_i + \varepsilon_i$
M6	$LnVls_i = \beta_0 + (\beta_1 + b_{1i})Lnd_i + \beta_2 LnV_i + \varepsilon_i$
M7	$LnVls_i = \beta_0 + (\beta_1 + b_{1i})Lnd_i + (\beta_2 + b_{2i})LnV_i + \varepsilon_i$
M8	$LnVls_i = (\beta_0 + a_i) + \beta_1 Lnd_i + (\beta_2 + b_{2i})LnV_i + \varepsilon_i$

Where: β_0, β_1 and β_2 = fixed model parameters; a_i = random intercept for the i-th species; b_{1i} *and* b_{2i} = random slope coefficients for the i-th species.

The structure of the mixed linear model used has the following form (WU, 2009):

$$y_i = X_i\beta + Z_i b_i + \varepsilon_i,\ i = 1, 2, \ldots, n.$$
$$b_i \sim N(0, G), \quad \varepsilon_i \sim N(0, R_i)$$

In which: X_i is the matrix that contains the covariables of individuals i, β are the fixed effects, Z_i is the matrix of random effects, b_i are the random effects, ε_i is the random error, G is the matrix of variance and covariance of random effects, R_i is the *nxn* matrix of residual covariance ($R_i = I \times \sigma^2$, where *I* is the identity matrix).

The fitting of the models referring to the mixed model were performed using the restricted Maximum Likelihood Method with the *nlme package* of the R software program. The statistical criteria of the equation were used in the fixed form to select the best functional form of the equation in the mixed form; however, instead of the adjusted coefficient of determination, the Akaike information criterion (AIC) was used.

The result of including the random effect in the intercept and in the slopes was verified using the maximum likelihood ratio test (RESENDE *et al.*, 2014), in which the significance of the difference (D) between the deviations [-2log(L)] for models with and without the random effect was verified by comparing the calculated value with the tabulated value by the χ^2 test at 5% significance. After selecting the best equation, the White test was applied to verify whether the residuals were homoscedastic.

RESULTS

Figure 1 shows the dispersion of the dendrometric variables log diameter, log length, sawn wood volume and total log volume, depending on the 9 species used in this study. The log length data showed the greatest heterogeneity and there is a variation between species. *D. excelsa* has the largest dimensions compared to the other species, which have similar dimensions, but some outliers can be observed. This heterogeneity of data only reinforces the use of mixed models, as the use of traditional modeling in this type of data will generate an equation with biased estimates, while the mixed model will correct these biases.

The equation fitted in the fixed form presented all the significant parameters, however, not all the equations in the mixed form presented the estimates of the statistically significant parameters for the fixed effects. All equations only showed significance in β_2. (Table 2).

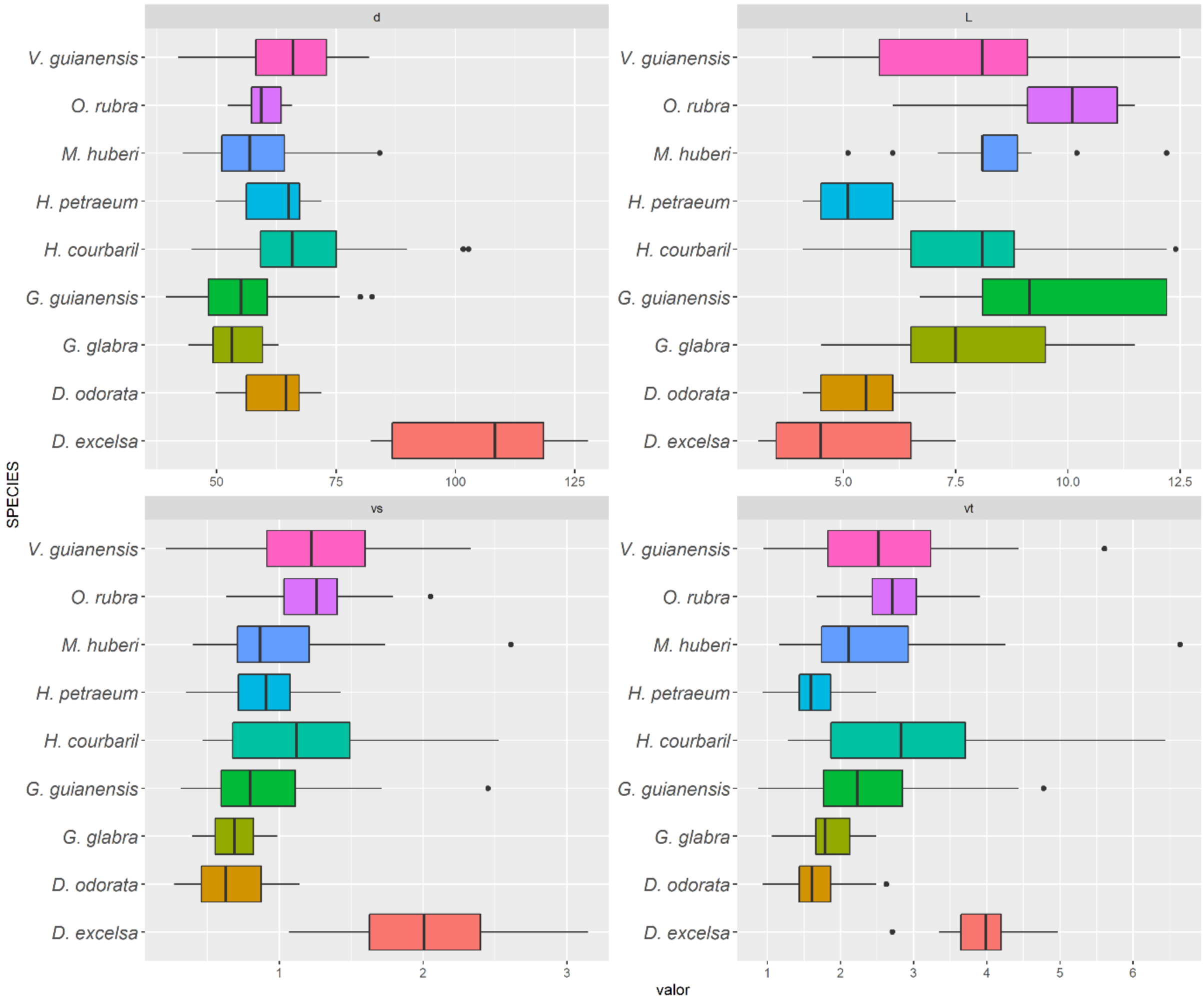

Figure 1. Boxplot of dendrometric variables used to fit fixed and mixed models for the 9 species under study. Value: variation of each variable on the x axis, d = average log diameter cm, L = log length, Vls = sawn wood volume in m³ and V = total log volume.

Figura 1. Boxplot das variáveis dendrométricas utilizadas para o ajuste de modelos fixo e misto para as 9 espécies em estudo. Valor: variação de cada variável no eixo x, d = diâmetro médio da tora cm, L = comprimento da tora, vs = volume de madeira serrada em m³ e vt = volume total da tora.

Table 2. Fixed parameters (β_0, β_1 and β_2) of the equations fitted in fixed and mixed form.
Tabela 2. Parâmetros fixos (β0, β1e β2) das equações ajustadas na forma fixa e mista

	Fixed Model	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-1.8751930	<0.0001
β_1	0.2606479	<0.0001
β_2	0.9191157	<0.0001
	M2	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.0575536	0.8833
β_1	-0.2050394	0.0434
β_2	1.0590521	<0.0001
	M3	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.0848784	0.8283
β_1	-0.1898418	0.0567
β_2	1.0167459	<0.0001
	M4	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.0848785	0.8283
β_1	-0.1898417	0.0567
β_2	1.0167459	<0.0001
	M5	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.2503029	0.5062
β_1	-0.1566568	0.1057
β_2	1.0497235	<0.0001
	M6	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.1301842	0.7393
β_1	-0.1806283	0.0745
β_2	1.0207289	<0.0001
	M7	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.0575536	0.8833
β_1	-0.2050394	0.0434
β_2	1.0590521	<0.0001
	M8	
Coefficient	$\hat{\beta}j$	**P value**
β_o	-0.0354431	0.9282
β_1	-0.2073669	0.0385
β_2	1.0480438	<0.0001

The volume equation in fixed form presented the Akaike 84.34 information criterion; correlation of 83.06%; mean of absolute differences 0.21; Bias -0.03; square root of the mean square error 0.30; and graphical distribution of the residuals tending to homogeneity (Figure 2). The equation presented a good fit, however a gain in the equation accuracy was obtained when the random effects were inserted, since all structures of mixed models present better statistics than the fixed effect model (Table 3).

The equations with random effects were all superior to the equation in fixed form. The equation with the lowest AIC (M7) uses the random effect in variables *d* and *V*. In analyzing the other statistics, it appears that M7 is superior to the others and equal to the M2 equation; however, its lower AIC indicates that M7 is more parsimonious than M2.

Table 3. Estimates of the precision statistics of the model in mixed form.
Tabela 3. Estimativas das estatísticas de precisão do modelo na forma mista

Model structure	AIC	$r_{y\hat{y}}$ %	MAD	BIAS	RMSE
M2	-3.50185	88.65	0.1733	0.0255	0.2517
M3	-0.19566	88.06	0.1774	0.0259	0.2577
M4	-2.19566	88.06	0.1774	0.0259	0.2577
M5	16.68467	87.55	0.1806	0.0260	0.2627
M6	-1.29386	87.78	0.1785	0.0260	0.2604
M7	-5.50185	88.65	0.1733	0.0255	0.2517
M8	-4.12673	88.58	0.1739	0.0256	0.2524

Where: AIC = Akaike information criterion; $r_{y\hat{y}}$ = correlation coefficient; MAD = mean of absolute differences; BIAS = calculates the average value by which the real is greater than expected; RMSE = square root of the mean square error

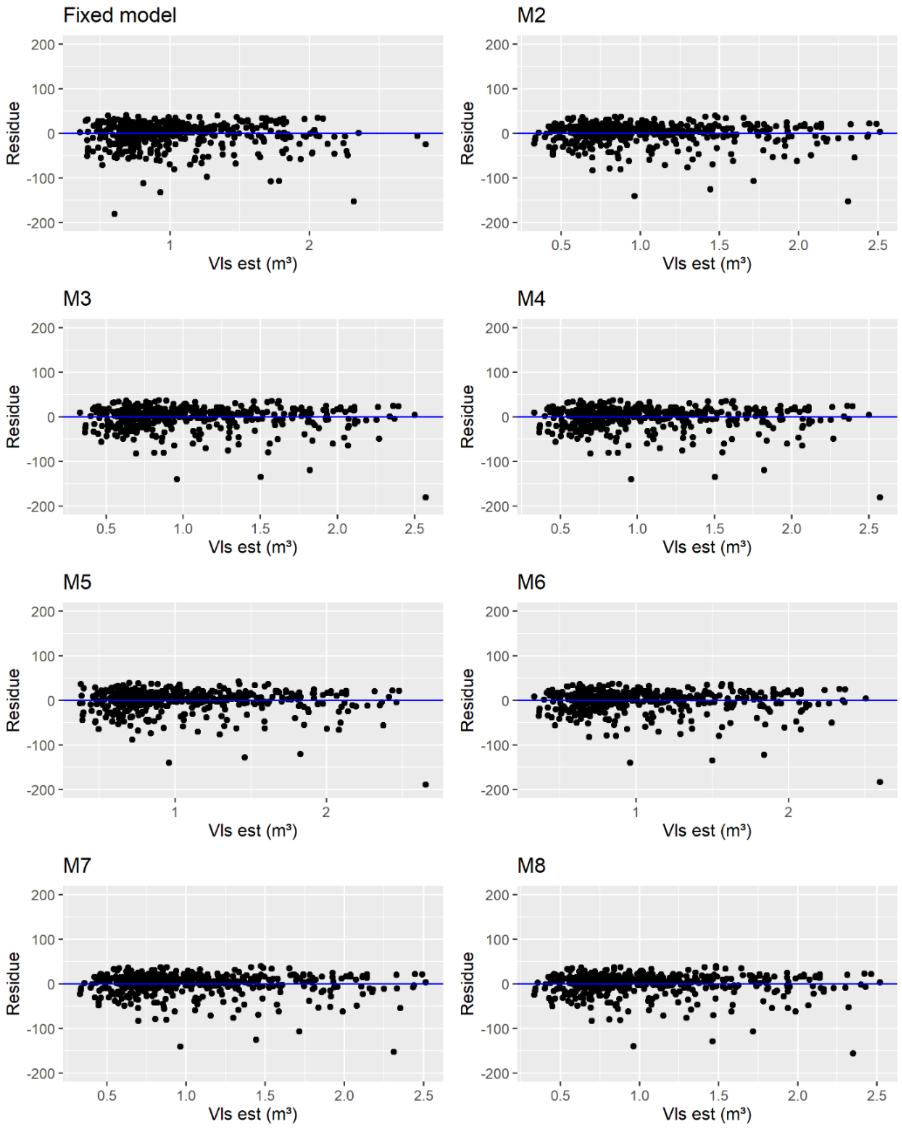

Figure 2. Graphical distribution of residuals for the equations in fixed and mixed form.
Figura 2. Distribuição gráfica dos resíduos para as equações na forma fixa e mista.

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It is observed that the residuals were well distributed, with an average around zero and constant variance, meaning that the assumption of homogeneity in relation to the observations for the equation with random effects on the *d* and *V* is not rejected (White test. = 67.78; p = 0.6190). Only four observations appear as outliers, meaning outside the confidence limits of -100 to 100% (Figure 2).

Through the maximum likelihood ratio test, it was found that the inclusion of the species as a random effect was significant (p> 0.05) in all equations, meaning that the random effects improve the accuracy of a model with only fixed parameters. Thus, being the final equation, it resulted in an equation with fixed and random effects (Table 4).

Table 4. Maximum likelihood ratio test.
Tabela 4. Teste de razão da máxima verossimilhança

Model	Maximum Likelihood	Test	Maximum Likelihood Ratio	p-value
M2	8.75093	F vs M2	93.8499	<0.0001
M3	6.09783	F vs M3	88.5437	<0.0001
M4	6.09783	F vs M4	88.5437	<0.0001
M5	-3.34233	F vs M5	69.6634	<0.0001
M6	5.64693	F vs M6	87.6419	<0.0001
M7	8.75093	F vs M7	93.8499	<0.0001
M8	8.06336	F vs M8	92.4747	<0.0001
Fixed	-38.17403			

The random effects by species of the equation with random effect in d and vt (M7) are shown in Figure 3 and the respective equations by species taking into account the random effects. Above is the estimate of the best model and the presence of great heterogeneity is observed. Below are the estimated values versus the observed values that follow the 45º line.

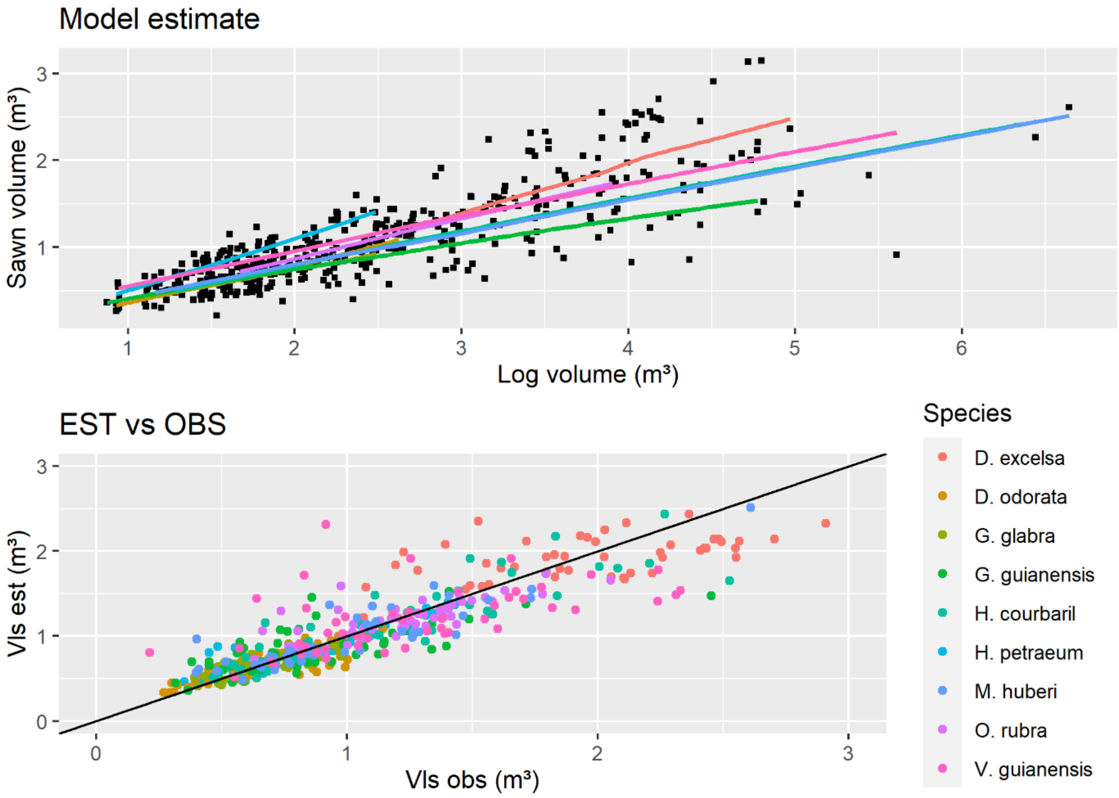

Figure 3. Estimation of the best model of random effect on total volume and estimated and observed value for the nine species under study.
Figura 3. Estimativa do melhor modelo de efeito aleatório sobre volume total e relação valor estimado e observado para as nove espécies em estudo.

Table 5 shows the fitted equations with the inclusion of mixed random effects for the 9 species used in the study.

Table 5. Equations with random effect by species.
Tabela 5. Equações com efeito aleatório por espécie

Species	Equation
D. excelsa	$LnVls_{D.e} = -0.0575536 - 0.2006057Lnd_{D.e} + 1.194736LnV_{D.e}$
D. odorata	$LnVls_{D.o} = -0.0575536 - 0.2407612Lnd_{D.o} + 0.134638LnV_{D.o}$
G. glabra	$LnVls_{G.g} = -0.0575536 - 0.2292573Lnd_{G.g} - 0.080468LnV_{G.g}$
G. guianensis	$LnVls_{G.gu} = -0.0575536 - 0.2256884Lnd_{G.gu} - 0.11975LnV_{G.gu}$
H. coubaril	$LnVls_{H.c} = -0.0575536 - 0.22426104Lnd_{H.c} + 0.005702LnV_{H.c}$
H. petraeum	$LnVls_{H.p} = -0.0575536 - 0.15819456Lnd_{H.p} + 0.117263LnV_{H.p}$
O. huberi	$LnVls_{O.h} = -0.0575536 - 0.21957272Lnd_{O.h} - 0.027907LnV_{O.h}$
O. rubra	$LnVls_{O.r} = -0.0575536 - 0.203253963Lnd_{O.r} + 0.012761LnV_{O.r}$
V. guianensis	$LnVls_{V.g} = -0.0575536 - 0.143759811Lnd_{V.g} - 0.177924LnV_{V.g}$

DISCUSSION

All the different mixed model configurations had great statistics. In a study by Gouveia *et al.* (2015) for volume estimates of *Eucalyptus* clones using mixed models, the model which best fit the data was model 7 with random effects according to AIC and RSME criteria, as it presented the lowest values, similarly to this study.

According to Dantas *et al.* (2020), the classic linear model employed as a device of many estimates presents some restrictions of use due to the assumptions, such as the independence of the observations and the homogeneity of variances, which are often not met.

It was verified by White's test that the hypothesis was met for the mixed form model, with homogeneous variance of residuals being different from the fixed model, which presented heterogonous variance. Thus, we can verify that the mixed model is an alternative for modeling in native Amazonian forests, as it is possible to estimate the volume of sawn wood by species and with more precision.

Situations in which data show heterogeneous behavior are common within forestry sciences when the response variable refers to proportions; there are also situations with very high residuals, indicating that it is not well-adjusted by the fixed regression. These characteristics are common in data from native Amazonian forests, and the residuals from the models for volume, height and other dendrometric variables have heteroscedastic residuals, so the mixed models fitted in this study were able to correct these problems for this database, so that all formulations presented lower error amplitude than the fixed model.

The models fitted herein can provide verification of productivity by species, offer opportunities for studying more accurate methods to estimate the present and future volume of a forest, and/or of the wood after its extraction. It is an alternative to fitting the conventional model which only considers the observed fixed effects, which could also be mixed linear and non-linear models (VISMARA *et al.*, 2015; BARROS *et al.*, 2021). Such models are adequate for analyzing repeated measures over time when this information is available, as they are adapted to unbalanced or incomplete data.

Mixed-effect models are used to describe the relationship between a response variable and one or more covariables in data grouped according to one or more factors, such as longitudinal data, repeated measurements, data with hierarchical structure and planning with blocks (PINHEIRO *et al.*, 2020). In this case, the wood logs were grouped into species, with our factors or effects being random, and by the maximum likelihood ratio test it was possible to verify that it was possible to have a random effect in all the different mixed model formulations, as all the equations were significant by the test. Studies with a mixed effect model used in the forest area in the Amazon are not common; the most recent work was carried out by Monteiro *et al.* (2021) for volume of fallen trees and found a better structure than the fixed model, similar to this study for lumber. This is one of the first studies that applies the use of mixed models for sawn wood volume and we can see that the results were satisfactory.

The works developed using mixed models for sawn wood are almost nonexistent. Within the national scenario in which the production of sawmill wood is strong, a greater dedication of research that can offer information to be used for better volume estimates is necessary, thereby assisting in production, optimizing business planning, and contributing to sustainable cycles of wood use, minimizing the loss of raw material and thus increasing yield.

Only nine commercial species from the Amazon were used for this study; however, the same study can be replicated for more species from the Amazon, but also from different formations within the Amazon Forest such as the estuarine floodplain, igapó, cerrado and other formations in Brazil. In addition to volume, mixed models can be used for all dendrometric variables, since behavior in all the data will be heterogeneous. Thus, it would be possible to generate several equations per species from a mixed model with a refined approach. In addition to species, families, soil type, forest strata, and terrain topography can also be inserted as random effects, among other categorical variables.

CONCLUSION

- The use of the fixed model had a lower efficiency and precision when considering the random effect models, which had superior performance according to the square root criterion of the mean square error (RMSE%) for the volumetric estimates and Akaike information criterion (AIC), and therefore the use of mixed models is recommended for volume estimates.
- Residuals improved substantially, with all mixed models showing a lower relative residual amplitude than the fixed model.
- The M7 model provided the best fit among the mixed models analyzed, with the lowest values of RMSE and AIC, and the model was effective in fitting the equations for the 9 studied species.
- With the mixed model, it is possible to estimate the volume of sawn wood per log with greater accuracy and better financial return, since this model will estimate considering the data structure for each species and not a single equation for all species tending to the average.

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