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Original Article

Forest Management

Estimation of the Basic Wood Density of Native Species Using Mixed Linear Models

Jeferson Pereira Martins Silva[1], Márcia Rodrigues de Moura Fernandes[1], Anny Francielly Ataide Gonçalves[2], Isáira Leite e Lopes[2], Gilson Fernandes da Silva[1], Christian Dias Cabacinha[3]

[1]Universidade Federal do Espírito Santo – UFES, Jerônimo Monteiro/ES, Brasil
[2]Universidade Federal de Lavras – UFLA, Lavras/MG, Brasil
[3]Universidade Federal de Minas Gerais – UFMG, Montes Claros/MG, Brasil

ABSTRACT

This paper aimed to estimate the basic density (DB) of the wood of Cerrado species using mixed linear models. For performing the DBH measurement, the sampling of 334 individuals was carried out. By keeping the Pilodyn apparatus in the DBH position, two measurements were made on opposite sides. Further, for determining DB, the trees were knocked down, followed by removal of five wood discs at different height of stem positions. For this purpose, two sets of modeling alternatives were proposed, which take into account with and without random effects, employing species as a random effect grouping variable. Thus, it was elucidated that, for the estimation of DB, the mixed model that considered the random effects performed better as compared to the alternative model without random effects. The inclusion of random effects leads to the estimation of DB with high accuracy.

Keywords: Cerrado stricto sensu, wood quality, regression.

1. INTRODUCTION

Basic density (DB) is one of the most important parameters in the evaluation of the wood quality and its utility in wood industry (Rodriguez et al., 2016). However, it constitutes a complex variable as it results from the combination of several factors such as cell wall thickness, vessel volume, parenchyma, fiber size, wood heartwood, sapwood and arrangement of anatomical elements (Foelkel et al., 1971).

Further, depending on the utilization of this factor, one can estimate the forest biomass and carbon stock (Baccini et al., 2012; Saatchi et al., 2011). Thus, knowledge about this basic wood density (DB) of native species aids in the conservation and sustainable exploitation of forests (Chave et al., 2005, 2014; Jati et al., 2014; Djomo et al., 2016).

However, DB estimation is a challenge due to its variability (Leite et al., 2016) with several factors such as genetics (Kimberley et al., 2015), age (Githiomi & Kariuki, 2010; Sette et al., 2012), site (Meneses et al., 2015), environmental conditions, tree thinning (Latorraca & Albuquerque, 2000; Oliveira et al., 2012), among species (Vale et al., 2010) and inside the same tree (Henry et al., 2010; Wassenberg et al., 2015).

Generally, traditional regression models are involved in the DB modeling studies (Couto et al., 2013). It takes into consideration several assumptions, such as the independence between observations and homogeneity of variance. But these assumptions are not always fulfilled (Gouveia et al., 2015).

Thus, as an alternative, more accurate statistical techniques such as mixed models are used, which allows generalization of spatiotemporal correlations structures and non-constant variance. Moreover, in comparison to traditional regression models, the mixed models are capable of extracting the relationships of independent variables with clustered data (Calegario et al., 2005; Fausto et al., 2008; Gouveia et al., 2015).

The growing application of mixed models to solve regression problems has been successful in modeling the hypsometric relationship of (Gómez-García et al., 2016; Mendonça et al., 2015; Özçelik et al., 2018) growth in diameter (Bohora & Cao, 2014; Xu et al., 2014; Ruslandi et al., 2017), mortality (Groom et al., 2012; Zhang et al., 2015) biomass and volume (Meng et al., 2007; Bueno-López & Bevilacqua, 2012; Guangyi et al., 2015), and tree taper (Cao & Wang, 2011). Hence mixed models, which enhances the accuracy of the produced estimates, proves to be a potential technique for modeling the basic density of wood.

Thus, keeping in view the above points, the current investigation focusses on the exploitation of mixed linear models, in place of traditional regression models, for the evaluation of possible gains in accuracy of DB estimation.

2. MATERIAL AND METHODS

2.1. Location and characterization of area under examination

The study was carried out in a legal reserve area of 29.6 hectares, located at 16°41' S and 43°50' W coordinates in the municipality of Montes Claros (Figure 1). According to Köppen (Köppen & Geiger, 1928), the climate of the region is tropical wet-dry, also termed as Aw, with rainfall being mainly concentrated between October and March months. Further, the average annual precipitation and temperature were found to be 1,060 mm and 24.2 °C, respectively (INMET, 2013).

Out of 29.6 ha area under examination, just one-hectare area (100 m × 100 m) was chosen for the collection of the database (Figure 1), as it displays a continuous area with the maximum variability of the Cerrado phyto-physiognomy. In this selected area, all the woody trees having life, and diameter at breast height (DBH) equal to or greater than 3.0 cm, were further collected and identified with their respective botanical names. Additionally, the classification used in the present study, adopted at the family level, was according to APG III (2009).

In total, the evaluation of 334 living individuals (distributed in 13 species), not protected by the current legislation, with bark diameter at 1.30 m of soil height (DBH) equal to or greater than 3 cm. Further, in every individual were measured the DBH, total height (H), and resistance to penetration the Pilodyn apparatus[(PIL)] (Table 1).

Using the Pilodyn apparatus, the penetration resistance was evaluated in all selected individuals by carrying out two measurements on opposite sides of the DBH position under bark, which in turn assists in calculating the arithmetic mean of the penetration depth of the needle in every single individual under examination.

The basic density (DB) of the wood was procured by knocking down the selected trees, followed by removal of five wood discs of approximately 3.0 cm in thickness at 0%, 25%, 50%, 75% and 100% height positions of the tree stem. It was further defined, in the present work, as the height of the commercial stem growing from the ground level to a minimum diameter of 3 cm with the bark of the main stem of the tree being intact. Furthermore, the estimation of sample volume and dry weight was carried out in the laboratory, where the volume of the sample was calculated using the water displacement method, also

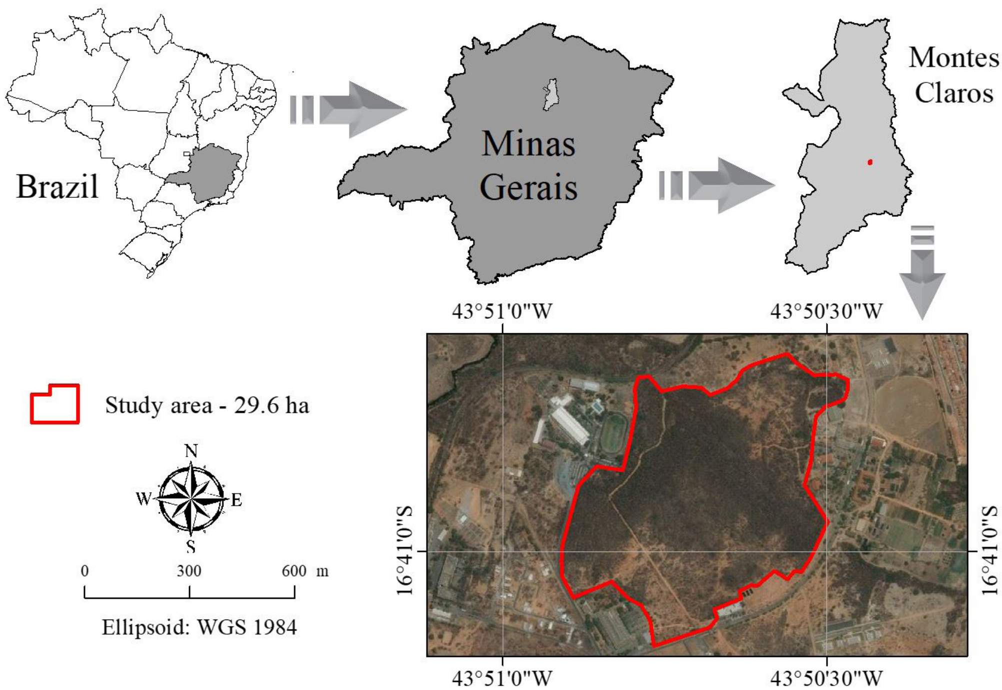

Figure 1. Location of the study area.

Table 1. Scientific name of the studied species, number of individuals sampled per species with minimum, medium, and maximum values of the diameter at breast height (DBH), total height (H), and resistance to penetration measured using the Pilodyn apparatus (PIL).

Species	Amount	DBH (cm)			H (m)			PIL (mm)		
		min	average	max	min	average	max	min	average	max
Luehea paniculata Mart. & Zucc	7	3.50	5.21	10.12	3.4	5.4	8.6	8.0	9.4	11.0
Terminalia fagifolia Mart. & Zucc	29	3.34	5.21	9.33	3.3	4.7	6.7	5.6	9.3	11.5
Copaifera langsdorffii Desf	20	3.02	6.56	13.96	3.2	5.6	8.9	7.5	9.9	15.0
Maytenus sp.	7	3.18	5.79	8.21	3.8	4.9	5.9	6.0	9.1	12.5
Heteropterys byrsonimifolia A. Juss	120	2.93	4.80	14.45	2.7	4.3	6.8	4.8	8.5	12.0
Tocoyena formosa Cham. & Schltdl	19	3.34	4.56	6.94	2.7	4.2	6.5	6.5	8.5	14.0
Machaerium opacum Vog.	55	3.50	6.19	16.39	1.9	4.0	6.3	4.2	7.0	10.5
Machaerium sp	7	3.92	5.45	7.32	3.9	6.8	8.8	6.5	8.0	9.0
Curatela americana L	22	3.72	6.39	13.81	2.0	3.5	5.8	8.5	13.4	18.0
Byrsonima heterophyla	13	3.25	6.43	12.11	3.2	4.7	6.2	5.5	10.3	14.5
Combretum leprosum Mart	12	3.63	5.37	10.82	3.0	4.1	5.5	7.8	11.2	13.5
Dalbergia brasiliensis Vog	20	3.02	5.69	10.89	3.1	5.0	7.3	7.0	10.1	12.5
Magonia pubescens A.St & Hil	7	3.02	4.52	7.00	3.3	4.3	5.9	6.5	7.5	9.0

known as the Archimedes principle. Subsequently, after drying all samples in a greenhouse at 103 °C, the dry weight of each sample was evaluated (ASTM, 2002). Thus, the ratio of the dry weight to the volume of the sample obtained illustrates the DB of the wood at each sampled position. By further calculating the arithmetic mean of the densities in each longitudinal position, the DB of the wood of each tree was estimated.

2.2. Rated models

To further validate whether the accuracy of the wood DB estimation of Cerrado native species will improve by the inclusion of the random effect (species), the regression models were adjusted with fixed effect (Equations 1, 2, 3, 4, 5, and 6) and also in the mixed form (Equations 7, 8, 9, 10, 11 and 12).

$$DB_{ij} = \alpha_0 + \alpha_1 PIL + \varepsilon_i \quad (1)$$

$$DB_{ij} = \alpha_0 + \alpha_2 DBH + \varepsilon_i \quad (2)$$

$$DB_{ij} = \alpha_0 + \alpha_3 H + \varepsilon_i \quad (3)$$

$$DB_{ij} = \alpha_0 + \alpha_1 PIL + \alpha_2 DBH + \varepsilon_i \quad (4)$$

$$DB_{ij} = \alpha_0 + \alpha_1 PIL + \alpha_3 H + \varepsilon_i \quad (5)$$

$$DB_{ij} = \alpha_0 + \alpha_1 PIL + \alpha_2 DBH + \alpha_3 H + \varepsilon_i \quad (6)$$

$$DB_{ij} = (\beta_{00} + \gamma_{0j}) + (\beta_{01} + \gamma_{1j}) PIL \varepsilon_{ij} \quad (7)$$

$$DB_{ij} = (\beta_{00} + \gamma_{0j}) + (\beta_{02} + \gamma_{2j}) DBH + \varepsilon_{ij} \quad (8)$$

$$DB_{ij} = (\beta_{00} + \gamma_{0j}) + (\beta_{03} + \gamma_{3j}) H + \varepsilon_{ij} \quad (9)$$

$$DB_{ij} = (\beta_{00} + \gamma_{0j}) + (\beta_{01} + \gamma_{1j}) PIL + (\beta_{02} + \gamma_{2j}) DBH + \varepsilon_{ij} \quad (10)$$

$$DB_{ij} = (\beta_{00} + \gamma_{0j}) + (\beta_{01} + \gamma_{1j}) PIL + (\beta_{03} + H\gamma_{3j}) + \varepsilon_{ij} \quad (11)$$

$$DB_{ij} = (\beta_{00} + \gamma_{0j}) + (\beta_{01} + \gamma_{1j}) PIL + (\beta_{02} + \gamma_{2j}) DBH + (\beta_{03} + \gamma_{3j}) H + \varepsilon_{ij} \quad (12)$$

where: α_0, α_1, α_2 and α_3 = parameters of the fixed-effect model; β_{00}, β_{01}, β_{02}, β_{03} = fixed parameters of the mixed model; γ_{0j}, γ_{1j}, γ_{2j} and γ_{3j} = random parameters of the mixed model; DB_{ij} = random parameters of the mixed model; PIL = Pylodin; *DBH* = diameter at breast height; *H* = total height; ε_{ij} = random error.

The models 1 to 6 were adjusted by the ordinary least squares method in R software with the function lm. For the adjustment of the mixed linear models (Models 7 to 12), the maximum likelihood algorithm was used. The type of variance and covariance structure chosen was the diagonal, available in the software package nlme R (R Development Core Team, 2018).

2.3. Methods for evaluation of estimates accuracy

Based on the species, data were separated randomly at 70% for fit and 30% for validation. Further, depending on the following statistics: adjusted coefficient of determination ($\bar{R}^2$), relative bias [B (%)], and relative root mean square error [RMSE (%)] (Equations 13, 14 and 15; Table 2), the estimates generated by the mixed models and the model with only fixed effects were evaluated for both the adjustment and the validation (Table 2).

Table 2. Statistics to evaluate the performance of mixed models and multiple linear regression in the estimation of the DB of the Cerrado wood species.

Statistics	Formulas	Nº
Adjusted coefficient of determination	$\bar{R}^2 = 1 - \left(\frac{n-1}{n-p}\right)\left[1 - \left(1 - \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}_i\right)^2}\right)\right]$	(13)
relative bias	$B(\%) = \frac{100}{\bar{Y}} \frac{\sum_{i=1}^{n} Y_i - \sum_{i=1}^{n} \hat{Y}_i}{n}$	(14)
Root mean square relative error	$RMSE(\%) = \frac{100}{\bar{Y}} \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n}}$	(15)

Y_i = dependent variable observed; $\hat{Y}_i$ = estimated dependent variable; $\bar{Y}_i$ = mean of the observed dependent variable; n = number of observations.

With the aim of further complementing the statistics, a graph was drawn using the values obtained and estimated by the techniques and graphs of percent residuals. Also, the error percentage of each observation was calculated using Equation 16, shown below:

$$E(\%) = \frac{Y_i - \hat{Y}_i}{Y_i} 100 \quad (16)$$

where: $E(\%)$ = percentage error of each observation.

3. RESULTS

Upon evaluation of the parameters significance for the multiple linear regression model with all fixed effects using the student t-test, exceptions regarding the parameters associated with DBH of model 2, and height (H) of models 3 and 6, were perceived. Whereas the significance level of all remaining parameters was found to be 5%, indicating their probability of occurring is 5%.

The coefficient associated with non-significant height was demonstrated for model 6 (Table 3). Thus, the most appropriate model for estimation of the basic wood density in the study region was model 4. Further, the prediction of regression statistics for models 4 and 6, using models with the fixed effects, was more accurate (Table 4).

The analysis of the statistics, employed for the corroboration of the mixed models performance regarding adjustment and validation of data (Table 5),

Table 3. Values of the coefficients of various models with fixed effects estimating the basic density of Cerrado wood species.

Model	Intercept	*PIL*	*DBH*	*H*
1	0.763422*	-0.017727*		
2	0.589491*		0.003167^{ns}	
3	0.590297*			0.003671^{ns}
4	0.736935*	-0.019765*	0.008264*	
5	0.734533*	-0.018225*		0.007518*
6	0.730152*	-0.019782*	0.007742*	0.002201^{ns}

^{ns} = not significant; PIL = Pylodin; DBH = diameter at breast height; H = total height; *significance level at 5% probability by the student t test.

Table 4. Statistics employed in adjustment and validation for evaluation of the models with fixed effects exploited for the estimation of the DB of Cerrado wood species.

Model	Fitting		Validation		
	RMSE%	$\bar{R}^2$	RMSE%	BIAS	$\bar{R}^2$
1	8.35	0.37	7.35	-0.14	0.47
2	10.40	0.01	10.43	0.93	0.00
3	10.48	0.00	10.34	0.85	0.00
4	7.86	0.44	7.64	-0.12	0.44
5	8.21	0.38	7.49	-0.22	0.45
6	7.85	0.43	7.67	-0.15	0.43

RMSE (%) = root mean square error; $\bar{R}^2$ = adjusted coefficient of determination; BIAS = relative bias.

Table 5. Statistics used in the adjustment and validation of data for evaluating the application of mixed linear models in the estimation of the DB of Cerrado wood species.

Model	Fitting			Validation		
	RMSE%	BIAS	$\bar{R}^2$	RMSE%	BIAS	$\bar{R}^2$
7	5.81	0.04	0.69	5.60	0.75	0.70
8	5.96	0.04	0.67	5.90	1.07	0.67
9	5.88	0.03	0.68	5.79	1.04	0.69
10	5.56	0.02	0.72	5.86	0.77	0.68
11	5.48	0.01	0.73	5.66	0.73	0.70
12	5.40	0.02	0.73	5.74	0.72	0.68

RMSE (%) = root mean square error; $\bar{R}^2$ = adjusted coefficient of determination; BIAS = relative bias.

revealed that all models impart low RMSE (%) and high B (%) values, thereby indicating that results obtained from all models are of good quality. Therefore, the estimation of the DB with good results can be carried out using any of the above models. However, in the present study preference was given to the Model 11 over the Model 4 (regression model with fixed effects only) for the estimation of the wood DB.

The values of fixed and random effects of Model 11 are presented in Table 6 and 7, respectively.

In the adjustment and validation, most of the data of Model 11 (Figure 2) are in close approximation to the 45° line (red line) as well as to the zero error line in the residual scatter plot in comparison to Model 4, with all fixed effects.

Figure 2 further reveals that in both adjustment and validation, histograms of model 11 demonstrated errors in more than 95% of the cases grouped in the class amplitude of ± 10%, whereas histograms of the multiple linear regression model (Model 4) presented errors in 85% of the cases grouped in the same interval.

4. DISCUSSION

The attainment of higher results, in terms of accuracy, in all models with random effects, in comparison to the regression model with only fixed effects, was validated from the analysis of statistical indicators [$\bar{R}^2$, RMSE (%) and B (%)]. The above observation can be attributed to the ability of mixed linear models to extract the relationships of independent variables with clustered data in a better way (species) as compared to traditional regression models (Calegario et al., 2005; Gouveia et al., 2015).

Thus, one of the primary advantages of the models including the random effects in their structure, compared to the fixed effect models, is the reduction of the residual standard error. This reduction was further reported by Gouveia et al. (2015), who studied the volume of wood in Eucalyptus clones. However, the reduction noted was only 26 times. On the other hand, in the current study, the RMSE reduced from 7.86% (Table 4) to 5.48% (Table 5), which elucidates a gain in accuracy of approximately 31.21%.

Table 6. Values of the fixed effects coefficients of Model 4 used for the estimation of the DB of Cerrado wood species.

	Value	Std.Error	t-value	p-value
(Intercept)	0.6309446	0.026086759	24.186392	0
PIL	-0.0068727	0.002453106	-2.801615	0.0055
H	0.0080633	0.003663857	2.200755	0.0288

Table 7. Values of the random effects coefficients of Model 11 employed for the estimation the basic density of Cerrado wood species.

Group	γ_{0j}	γ_{1j}	γ_{2j}
Luehea paniculata Mart. & Zucc	-0.00671568	-0.005109	-0.00024296
Terminalia fagifolia Mart. & Zucc	-0.04778732	0.0054803	0.00088041
Copaifera langsdorffii Desf	0.05640130	-0.006009	-0.00249756
Maytenus sp.	0.01573392	0.0022004	-0.00108434
Heteropterys byrsonimifolia A. Juss	-0.02077278	0.0024771	-0.00100297
Tocoyena formosa Cham. & Schltdl	0.00041378	0.0041583	-0.00088258
Machaerium opacum Vog.	0.04630224	0.0041536	-0.00154117
Machaerium sp	0.04079368	0.0031197	-0.01204169
Curatela americana L	-0.07278023	-0.004694	0.01215873
Byrsonima heterophyla	-0.00077800	-0.006311	0.00960528
Combretum leprosum Mart	-0.02528282	-0.002264	0.00252822
Dalbergia brasiliensis Vog	-0.06963246	0.0018974	0.00301561
Magonia pubescens A.St & Hil	0.084104259	0.0009007	-0.00889499

Where: γ_{0j}, γ_{1j}, γ_{2j}.

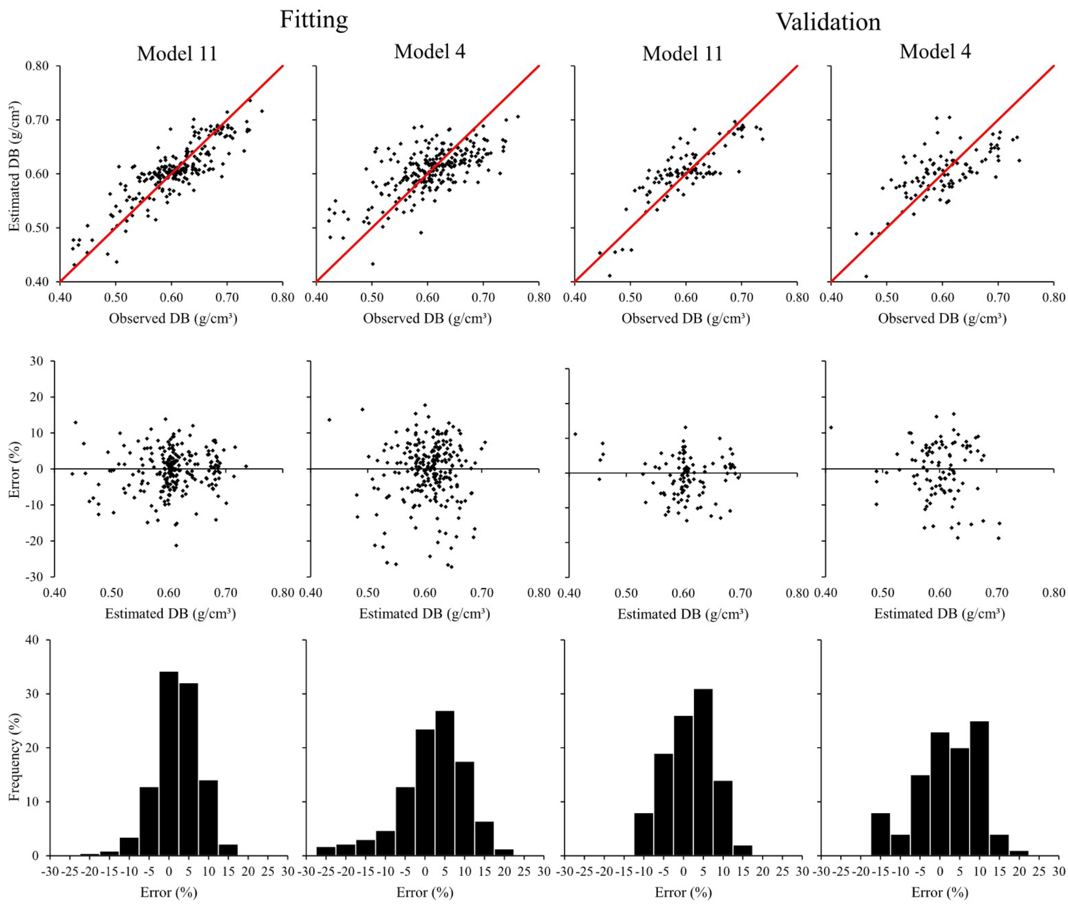

Figure 2. Graphs of observed DB versus estimated DB, residual scatter plot of error percentage as a function of estimated DB, and histogram of the frequency of percentage errors as estimated by Model 11 and Model 4 in the adjustment and validation sets.

The advantage of including the random component in the models was further validated from the residual dispersion graphs shown in Figure 2. Model 11, used to estimate the basic density (DB), presented better residual distribution around the zero error line in comparison to the multiple linear regression model with all fixed effects (Model 4), in both adjustment and validation.

Additionally, the mixed models proposed in the current work presented as a model with the random component of the species, where taking species into account for analysis, implies assigning of lines to each of the considered species, which in turn reduces the error committed by the species. Thus, one can deduce that, in the present investigation, the assignment of lines to each species is the main reason for the reduction of RMSE by 31.21% in Model 11 as compared to Model 4.

Since the basic wood density (DB) of native species is frequently used in the estimation of forest biomass and carbon stock, the knowledge about DB aids in the conservation and sustainable exploitation of forests. However, a well-defined behavior is not observed for DB, as it is difficult to estimate due to the variability between the different species. Thus, the use of more accurate statistical techniques, such as mixed models, is a good alternative as it is capable of capturing the relationships of independent variables with pooled data in a better way as compared to traditional regression models.

Further, the DB of wood varies between species (Chave et al., 2006; Maniatis et al., 2011), within the species, and within the tree itself (Wassenberg et al., 2015; Nock et al., 2009; Plourde et al., 2015; Osazuwa Peters et al., 2014; Henry et al., 2010; Deng et al., 2014). These variations are sizeable as well as the changes observed are in line with the tree sampling (Pádua et al., 2015). Additionally, studies involving the DB variation of wood of the genus *Eucalyptus* along with other species (e.g. Cruz et al., 2003) show an increase in the marrow-shell direction and a decrease in the base-top direction.

Thus, wrapping up the observations of the present study, one can state that the PIL, DBH, H, and species can affect the estimation of the basic density of the wood. Moreover, according to Ribeiro & Zani (1993), the genetic and environmental factors are responsible for variation in the DB of tree wood. Apart from this, the interaction between these two factors also exhibits repercussions on the DB of wood. This variation of DB due to the above factors, in turn, can explain the better performance of the models with random effects in comparison to regression models with fixed effects for the estimation of the basic density of Cerrado species.

Conclusively, the method used in the present investigation for estimating the DB of tree wood has great potential. Additionally, carrying out more studies with the combination of other variables in the mixed model, apart from those examined in this study (PIL, DBH, H, and species), can substantially increase the accuracy of the estimates. For example, in the study conducted by Silva et al. (2015), a strong relation (0.94) has been established between the basic wood density of the branches with that of the trunk density of 34 species in the Cerradão de Palmas. Further, harvesting of the trees is not essential for determining the DB of the branches, as the variable (twig density) could be an alternative to obtain more reliable estimates of the DB of wood. Alternatively, the modeling of variance heterogeneity and autocorrelation can also improve the accuracy of the estimate (Gouveia et al., 2015, Calegario et al., 2005).

5. CONCLUSION

In conclusion, the mixed linear models as a superior paradigm exhibited an evident gain in the accuracy of estimation of the basic density (DB) of Cerrado species in comparison to the linear regression model, which takes into account only fixed effects.

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Jeferson Pereira Martins Silva
Departamento de Ciências Florestais e da Madeira, Universidade Federal do Espírito Santo – UFES, Av. Governador Carlos Lindemberg, Centro, CEP 29550-000, Jerônimo Monteiro, ES, Brasil
e-mail: jefersonsb09@hotmail.com

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