

ORIGINAL ARTICLE

Effect of age on the hypsometric relationship in the young African mahogany population in the central region of Minas Gerais***Efeito da idade na relação hipsométrica em povoamento jovem de mogno africano na região central de Minas Gerais***

Juliana Fonseca Cardoso^{1*} , Artur Ferro de Souza¹ , Fernanda Beatriz Rocha Fernandes¹ ,
 Lucas Gabriel Souza Santos¹ , Guilherme Sávio Camargos Lima¹ , Eric Bastos Görgens¹ ,
 Gilciano Saraiva Nogueira² , Marcio Leles Romarco de Oliveira¹ , Renato Vinicius Oliveira Castro³ 

¹Universidade Federal dos Vales do Jequitinhonha e Mucuri – UFVJM, Diamantina, MG, Brasil

²Universidade Federal de Viçosa – UFV, Viçosa, MG, Brasil

³Universidade Federal de São João del-Rei – UFSJ, Sete Lagoas, MG, Brasil

ARTICLE INFO

Financial support: None.

Conflict of interest: Nothing to declare.

*Corresponding author:

juliana.cardoso@ufvjm.edu.br

Received: 2 December 2025.

Accepted: 17 June 2026.

Editor: Alexandre de Vicente Ferraz.

How to cite: Cardoso, J. F., Souza, A. F.,
 Fernandes, F. B. R., Santos, L. G. S.,
 Lima, G. S. C., Görgens, E. B., Nogueira, G. S.,
 Oliveira, M. L. R., & Castro, R. V. O. (2026).
 Effect of age on the hypsometric relationship
 in the young African mahogany population
 in the central region of Minas Gerais.
Scientia Forestalis, 54, e4188. <https://doi.org/10.18671/scifor.v54.15>

ABSTRACT

The cultivation of African mahogany (*Khaya* spp.) has expanded in Brazil. However, studies focused on the management and dendrometric characteristics of this species are still scarce. This study aimed to evaluate the influence of age on the height-diameter ratio in a young African mahogany stand. The data used for the study came from a 100% forest inventory from 2016 at 24 months of age, with remeasurements at 39, 53, 89 and 111 months, located in the municipality of Curvelo, Minas Gerais. Two approaches were evaluated: (Analysis 1) fitting four linear models with complete data, considering only diameter (original models) or diameter and age (adapted models); and (Analysis 2) fitting the original models for each age separately. When analyzing general models with and without the inclusion of the age variable, model 3.2 ($\ln H = \beta_0 + \beta_1 \ln DBH + \beta_2 \cdot AGE + \epsilon$) presented the best performance, highlighting the significant influence of age on the height-diameter ratio. In addition, when comparing the different models for the different age groups, Model 3 ($\ln H = \beta_0 + \beta_1 \ln DBH + \epsilon$) stood out as the most appropriate, presenting statistically significant differences ($p\text{-value} < 0.05$) between the age groups. These results demonstrate that age is a determining factor in the modeling of the height-diameter relationship for the African mahogany stand, and this strategy is more interesting than adjusting equations by age.

Keywords: Dendrometry; *Khaya* spp.; Dendrometry modeling; Forest inventory; Generalized linear models.

RESUMO

O cultivo de mogno africano (*Khaya* spp.) tem se expandido no Brasil. No entanto, estudos focados nas características de manejo e dendrométricas dessa espécie ainda são escassos. Este estudo teve como objetivo avaliar a influência da idade na relação altura-diâmetro em um povoamento jovem de mogno africano. Os dados utilizados para o estudo foram oriundos de um inventário florestal 100% de 2016 aos 24 meses de idade, com remedições aos 39, 53, 89 e 111 meses, localizado no município de Curvelo, Minas Gerais. Foram avaliadas duas abordagens: (Análise 1) ajustar quatro modelos lineares com dados completos, considerando apenas diâmetro (modelos originais) ou diâmetro e idade (modelos adaptados); e (Análise 2) ajustando os modelos originais para cada idade separadamente. Ao analisar modelos gerais com e sem a inclusão da variável idade, o modelo 3.2 ($\ln H = \beta_0 + \beta_1 \ln DBH + \beta_2 \cdot AGE + \epsilon$) apresentou o melhor desempenho, destacando a influência significativa da idade na relação altura-diâmetro. Além disso, ao comparar os diferentes modelos para as diferentes faixas etárias, o Modelo 3 ($\ln H = \beta_0 + \beta_1 \ln DBH + \epsilon$) destacou-se como o mais apropriado, apresentando diferenças estatisticamente significativas ($\text{valor-}p < 0,05$) entre os grupos etários. Esses resultados demonstram que a idade é um fator determinante na modelagem da relação altura-diâmetro para o povoamento de mogno africano, sendo mais interessante esta estratégia, do que ajustar equações por idade.

Palavras-chave: Dendrometria; *Khaya* spp.; Modelagem dendrométrica; Inventário florestal; Modelos lineares generalizados.



1. INTRODUCTION

The growing interest in the cultivation of African mahogany (*Khaya* spp.) has encouraged investments in several regions of Brazil (Ribeiro et al., 2017). Despite this, research on the management and biometric characteristics of this species in the country is still limited. Studies have addressed specific topics, such as growth under different irrigation regimes (Alves Júnior et al., 2016), transpiration measurements with thermal probes and lysimeters (Sérvulo et al., 2017), and the quality of plantations in monoculture and intercropping systems in the Eastern Amazon (Gonçalves et al., 2023). However, more specific information on the hypsometric modeling of young African mahogany stands is still needed, especially to support height estimates in growth and production studies.

In forest inventories, the height-diameter ratio is an essential tool for estimating the height of trees from diameter measurements, reducing field effort and operating costs (Machado and Figueiredo Filho, 2003; Rodriguez et al., 2010; Sanquetta et al., 2015). However, the precision and accuracy of the inventory are mainly associated with the method, process, and intensity of sampling (Nakajima et al., 2011; Miranda et al., 2022). Thus, in the context of hypsometric modeling, the appropriate choice of hypsometric models does not determine the accuracy of the inventory in isolation, but contributes to improving height estimates. Well-adjusted regression equations allow for more accurate estimates, optimizing time and reducing costs in data collection (Schneider et al., 2009).

Recent studies have expanded the knowledge about the hypsometric modeling of African mahogany in Brazil, focusing on the development and validation of equations for height estimation. Among these studies stand out: the evaluation of height prediction strategies in *Khaya ivorensis* stands using local and generalized models (Ribeiro et al., 2018); adjustments of hypsometric models for a three-year-old young *Khaya ivorensis* (Stolle et al., 2018); the modeling of the height-diameter relationship and the volume of *Khaya ivorensis* and *Khaya anthotheca* in agroforestry systems (Santos et al., 2019); and finally the evaluation of hypsometric models in commercial stands of *Khaya grandifoliola* (Matias et al., 2023). These studies reinforce the progress of research aimed at improving dendrometric estimates for species of the genus *Khaya*.

Although it is recognized that the height-diameter relationship varies with the age of the stand (de Azevedo et al., 1999), there is still limited information on how this relationship changes throughout the initial development of the same young stand of *Khaya grandifoliola*, especially based on successive remeasurements. Thus, the contribution of this study is not only to confirm that age influences the hypsometric relationship, but to quantify this effect over ages in a young stand of African mahogany (*Khaya grandifoliola* C. DC.), comparing models with and without the inclusion of age as an explanatory variable and to evaluate whether a single equation can adequately represent different stages of population development.

The work seeks to answer: (Q1) Which hypsometric models have the best fit? (Q2) Does the inclusion of age as an explanatory variable improve the predictive performance of general height-diameter equations? and (Q3): Is it feasible to use a single model for different ages?

Considering these issues, it is expected that the inclusion of age as an explanatory variable will increase the predictive performance of the models in relation to equations based only on diameter. It also assumes that the height-diameter relationship presents differences between the ages evaluated, indicating that equations adjusted for a specific age should not be applied indistinctly to other stages of development. In addition, models with greater

biological significance represent better the tall growth pattern of young African mahogany stands.

Thus, the objective of this study was to evaluate the influence of age on the hypsometric relationship of a young African mahogany (*Khaya grandifoliola* C. DC.) stand in the central region of Minas Gerais.

2. MATERIAL AND METHODS

The study area is located at Fazenda das Pedras (Figure 1), located in the municipality of Curvelo, central region of Minas Gerais, with the geographic coordinates 19°02'04" S 44°35'17" W, at an average altitude of 698 m. The Köppen climate classification is type Aw, characterized as tropical savanna with a dry season in winter (Alvares et al., 2013).

The stand of African Mahogany (*Khaya grandifoliola* C. DC.) occupies an area of 20 ha and was planted out in 2014, with a spacing of 5 x 5 m. The data used in this study were obtained from a 100% inventory (census) of individuals, in 2016, at 24 months of age, with remeasurements aged 39, 53, 89 and 111 months. These inventories provided information on the total height (*H*), in m, and the diameter at breast height (*DBH*), in cm, of each individual, obtained with the aid of the Haglöl hypsometer and tape measure, respectively.

For Analysis 1, we used the database with all measurements for height estimation, and four linear hypsometric models, considering two approaches: models that used only *DBH* for estimation (original model), and the model with *DBH* and age as explanatory variables (adapted model) (Figure 2).

The models were adjusted by the method of ordinary least squares, and diagnostic tests of the assumptions for the residuals were performed. The normality of the residuals was evaluated by the Shapiro-Wilk test, by the *Shapiro.test()* function of the *stats* package (Shapiro & Wilk, 1965; Midway & White, 2025), in the *R* software (version 4.5.0) (R Core Team, 2025). Heteroscedasticity was verified by the Breusch-Pagan tests (Breusch & Pagan, 1979; Velten et al., 2024), using the *bptest()* function of the *lmtest* package (Zeileis & Hothorn, 2002), and White, applied by auxiliary regression of the quadratic residuals as a function of the adjusted values and their quadratic terms (White, 1980). The multicollinearity between the explanatory variables was analyzed by the variance inflation factor (VIF) (<10) (Gujarati & Porter, 2011) using the *vif()* function of the *car* package (Fox & Weisberg, 2019).

In quadratic models, *DBH* was centralized before the inclusion of the term *DBH*², in order to reduce the non-essential collinearity between linear and quadratic terms (Dalal & Zickar, 2012; Lacobucci et al., 2016). Detecting the violation of any of the assumptions evaluated, the models were readjusted by weighted least squares (Gregoire & Dyer, 1989).

The selection of the best model was based on the biological realism of the trend of estimating *H* as a function of *DBH*, followed by the result of quality statistics: adjusted coefficient of determination (*R*²_{aj}), standard error of estimation (SEE) and coefficient of variation (CV). In logarithmic models, the estimates were transformed to the original height scale and corrected by the Meyer factor (Meyer, 1941; Schneider et al., 2009), allowing the comparison of fit statistics in the same unit of the response variable.

Finally, the model identity test proposed by Graybill (1976) was performed, comparing the original model and the model adapted to the model with the best height estimate, in order to identify the influence of the age variable. The level of significance adopted was 5% ($\alpha = 0.05$). For Analysis 2, we used the database at each age separately to estimate heights, with the original model of the four models previously used (Figure 3).

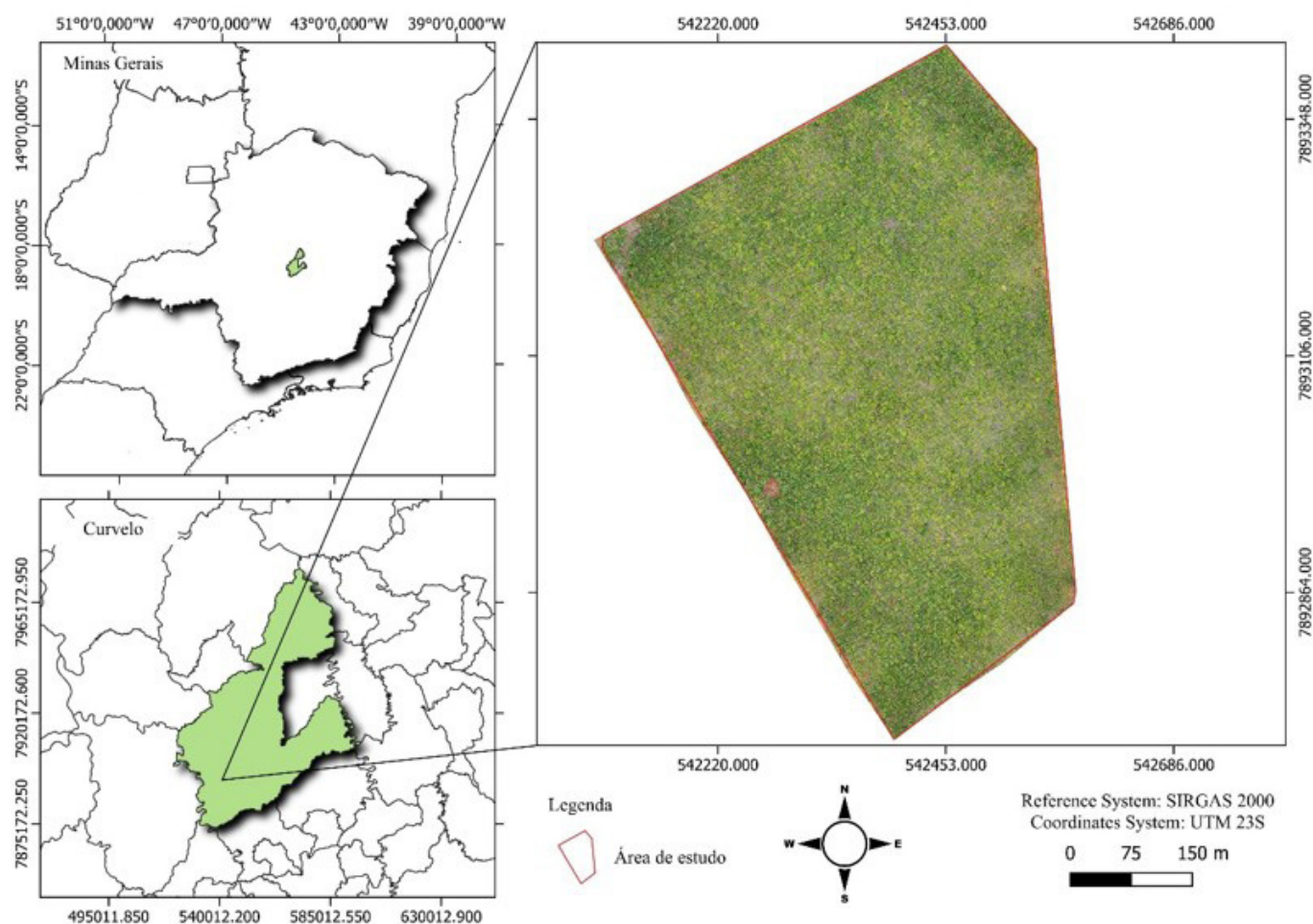


Figure 1: Area of the African Mahogany (*Khaya grandifoliola* C. DC.) stand at Fazenda das Pedras, Curvelo-MG.

The selection of the best model was based on biological realism, and the result was quality statistics (R^2_{aj} , SEE, CV%). The likelihood ratio test (LRT) was used to compare nested models and verify whether a single equation could adequately represent the height-diameter relationship at the different ages evaluated. The test statistics were calculated from the difference between the log-likelihoods of the models, obtained by the *logLik()* function of the *stats* package, and its significance was evaluated by the chi-square distribution, using the *pchisq()* function.

3. RESULTS

3.1. Influence of the age variable on the hypsometric model

The diagnostic tests showed deviations in the assumptions of the models initially adjusted by the ordinary least squares method. The Shapiro-Wilk test indicated no normality of the residuals for all models ($p < 0.05$). The Breusch-Pagan and White tests were also significant for the models evaluated ($p < 0.05$), indicating the presence of heteroscedasticity and justifying the readjustment by weighted least squares. The multicollinearity analysis indicated a VIF lower than 10 for most models, ranging from 2.66 to 8.16. Only model 4.2 presented a VIF greater than 10 for one of the terms (VIF = 11.74), although the centralization of the DBH reduced the collinearity between the linear and quadratic terms.

The models adjusted by the weighted minima method showed good performance for the height estimate, with an adjusted coefficient of determination above 0.77. The analysis of the quality statistics shows that the inclusion of the age variable improved the predictive performance of the equations. The adapted model (4.2) showed better overall performance, corroborated by the high explanatory power ($R^2_{aj} = 0.87$) and low residual dispersion (SEE = 2.11 m; CV = 18.50%). On the other hand, model (2.1) was the one with the lowest performance when compared to the statistics of the other models (Table 1).

Although the weighted least squares adjustment was adopted to reduce the effects of heteroscedasticity on the estimation of the coefficients, the graphical analysis of the residuals still showed important differences between the functional forms of the models, especially regarding the presence of clusters, systematic trends, and dispersion in certain ranges of estimated height (Figure 4).

The dispersion of the residuals of model 1.1 showed a systematic trend of the residuals, especially at the lowest estimated heights, evidencing the limitation of the simple linear shape to represent the height-diameter relationship in the entire range of the data. The inclusion of age in model 1.2 reduced part of this pattern, although residual dispersion was still observed in some estimated height ranges.

Models 2.1 and 2.2 were unsatisfactory, with discontinuous distribution of waste. However, model 3.1 showed better homogenization of the residues, a trend according to the biological behavior of growth in height of the trees.

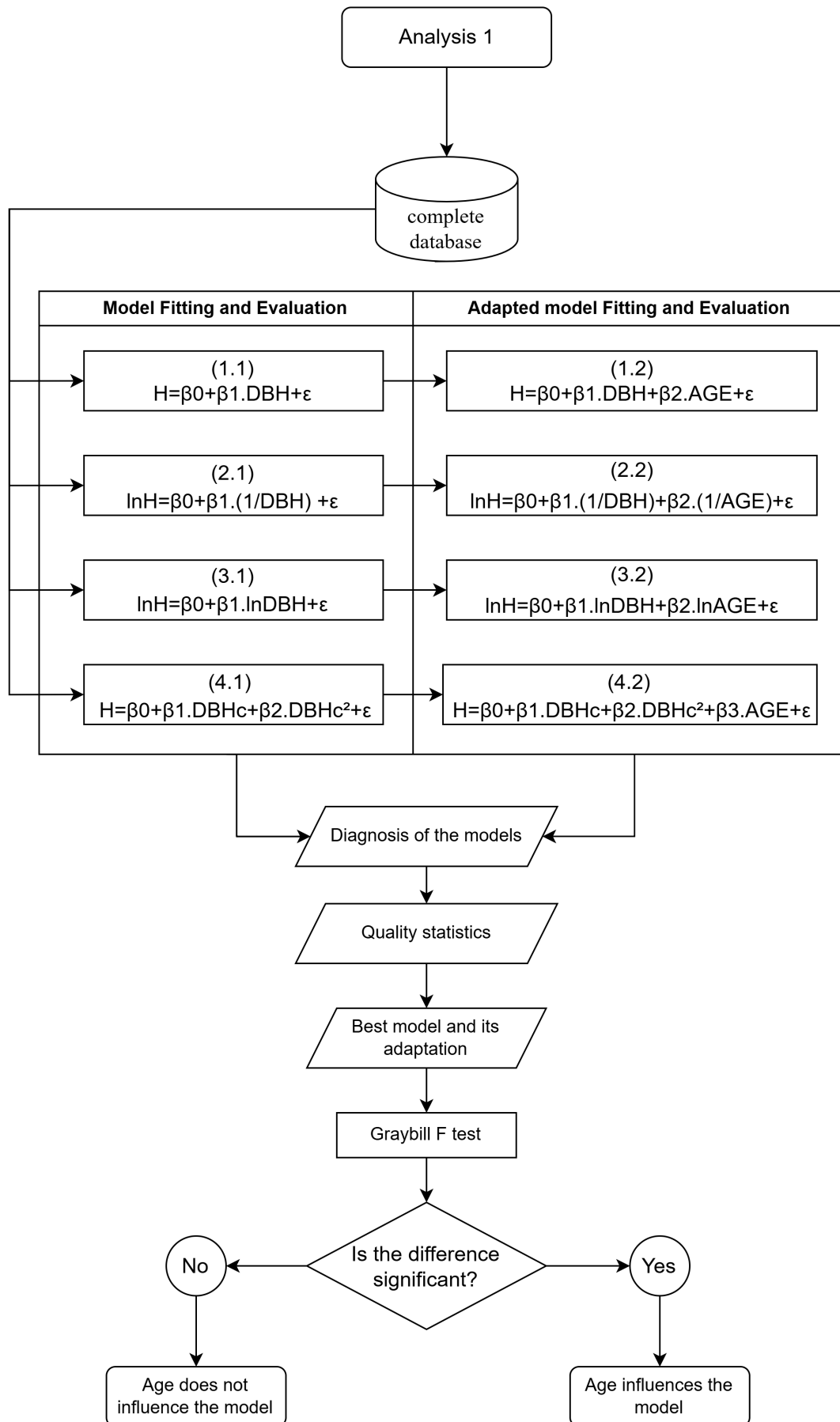


Figure 2: Workflow summary for Analysis 1.

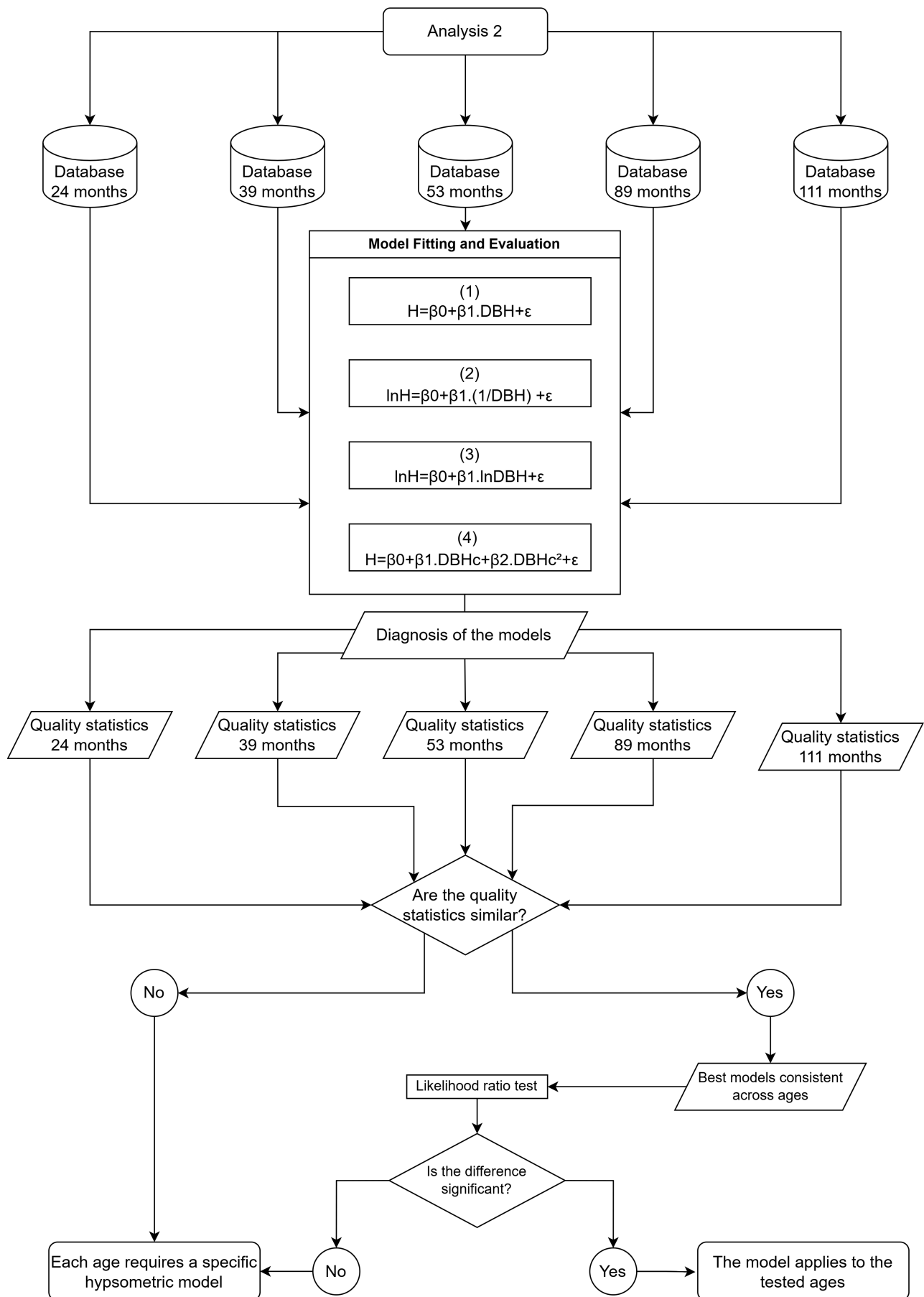


Figure 3: Workflow summary for Analysis 2.

The inclusion of age in the model (3.2) improves the predictive capacity by capturing the difference in tree growth over time. While models 4.1 and 4.2 show a reduction in bias observed in model 1.1, due to its quadratic

shape, it cannot accurately represent the height estimate, especially for smaller trees (Figure 4). Models 1.2 and 2.2 showed clustered patterns in the distribution of residuals, indicating the grouping of estimates by age.

Table 1: Estimated parameters for the models adjusted by the weighted least squares method and fit statistics of the original and adapted models, from Analysis 1.

Model	β_0	β_1	β_2	β_3	R^2_{aj}	SEE	CV%
(1.1) $H = \beta_0 + \beta_1 DBH + \varepsilon$	-0.2789*	0.8273*	-	-	0.83	2.42	21.25
(1.2) $H = \beta_0 + \beta_1 DBH + \beta_2 AGE + \varepsilon$	-0.6493*	0.5517*	0.0683*	-	0.86	2.20	19.32
(2.1) $\ln H = \beta_0 + \beta_1 (1/DBH) + \varepsilon$	3.0945*	-8.4224*	-	-	0.77	2.86	25.05
(2.2) $\ln H = \beta_0 + \beta_1 (1/DBH) + \beta_2 (1/AGE) + \varepsilon$	3.3004*	-2.4101*	-37.4711*	-	0.85	2.30	20.16
(3.1) $\ln H = \beta_0 + \beta_1 \ln DBH + \varepsilon$	-0.3256*	1.0351*	-	-	0.83	2.44	21.36
(3.2) $\ln H = \beta_0 + \beta_1 \ln DBH + \beta_2 \ln AGE + \varepsilon$	-0.9935*	0.7259*	0.3603*	-	0.86	2.26	19.81
(4.1) $H = \beta_0 + \beta_1 DBH + \beta_2 DBH^2 + \varepsilon$	11.0383*	0.8170*	0.0064*	-	0.82	2.50	21.92
(4.2) $H = \beta_0 + \beta_1 DBH + \beta_2 DBH^2 + \beta_3 AGE + \varepsilon$	6.0207*	0.4193*	-0.0091*	0.0921*	0.87	2.11	18.50

Where: (*) indicate significant results by the t-test with a p-value < 0.05.

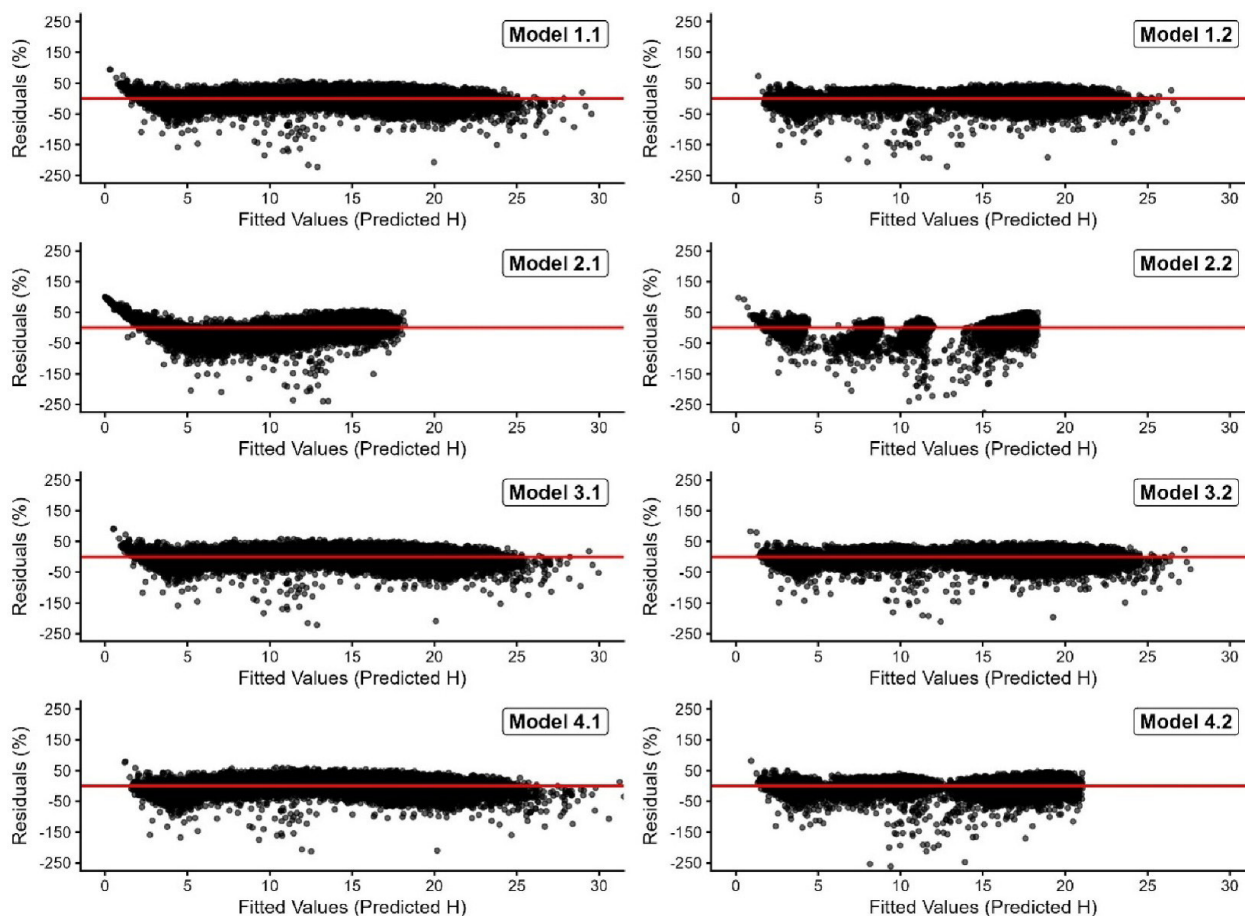


Figure 4: Dispersion of percentage residuals as a function of height estimates (H). for the original models (1.1, 2.1, 3.1 and 4.1) and adapted models (1.2, 2.2, 3.2 and 4.2), adjusted by the weighted least squares method, in Analysis 1.

Models 3.1 and 3.2 showed better performance, due to their biological realism, statistics, and dispersion of the residuals. Mathematically, the logarithmic transformation of the model (3.1) allows stabilizing the variance of the errors, capturing a global trend of the height estimate. The inclusion of age in the model (3.2) allows us to capture the intraclass variations of heights, ignored by the model that considers only *DBH* increases biological realism, translating the asymptotic behavior of growth in height of arboreal individuals (Figure 5).

The identity test of the Graybill F model showed that the addition of the age variable contributes significantly ($F = 7,305.84$; $p < 0.001$) to the height estimates, with an absolute mean percentage difference (MAPE) between the two models of 5.54%, indicating that the complete model estimates the heights more accurately than the observed values. This emphasizes the importance of considering the age of trees in hypsometric models.

3.2. Modeling by age of the stand

Hypsometric models adjusted separately by age, by weighted least squares, show variations in the explanatory capacity and accuracy of the models as trees grow (Table 2). All models showed significant parameters (p -value < 0.05).

In general, the models showed an adjusted coefficient of determination (R^2_{aj}) that was moderate for early ages (24 and 39) and low as age advanced (53, 89 and 111). This behavior indicates that, with advancing age, the height-to-diameter ratio becomes more variable and less explained by diameter alone.

The precision in the adjustments of the models had a similar behavior, with better precision in the estimates for young trees to the detriment of older ones. Suggesting that as trees grow, the height-to-diameter ratio becomes more complex, requiring the inclusion of additional variables to maintain the accuracy of the estimates.

The analysis of the percentage residuals of the weighted models, adjusted separately for age, revealed differences in the dispersion pattern between the hypsometric equations tested (Figure 6).

The fit of model 1 showed greater dispersion of the residues at the lowest estimated heights, especially at the initial ages, indicating a limitation of the simple linear shape to represent the full amplitude of the height-diameter relationship. The same behavior is expressed by model 2, indicating that both models cannot adequately capture the initial phase and stabilization of tree growth over time, reflecting the limitation of the mathematical form of model 1 in relation to the nonlinear pattern of tree growth, and the mathematical rigidity of model 2.

Model 3, adjusted for ages 24 and 39 months, showed more balanced dispersed residuals, and overestimation of heights at older ages (53, 89 and 111). The logarithmic form expresses growth close to biological realism, but with bias as trees age, demonstrating that the model does not have the flexibility to capture all hypsometric curvatures at older ages.

For ages 39 and 111, the intercept parameters (β_0) and 24 months for β_2 were not significant (p -value > 0.05) in model 4, although the results of quality statistics were satisfactory when compared to the other models (Table 2). In addition, there is a limitation of the model in estimating higher height values, a characteristic linked to the mathematical structure of the model. The introduction of the quadratic term in model 4 ($\beta_2 \cdot DBH^2$) allows capturing the asymptotic trend of taller trees, this characteristic underestimate the estimates of larger trees, identified by the flattening of the residues for trees larger than 15 meters in height.

Through these results, model (3) $\ln H = \beta_0 + \beta_1 \cdot \ln DBH + \epsilon$ was selected as the one that best estimates tree heights at different ages, due to its biological realism in height estimates. Despite the reduction in precision and accuracy at heights with an increase in the age range of the trees, this aspect supports the hypothesis of the need to add other dendrometric variables to the model, for better accuracy of the estimates.

Thus, model 3 was submitted to the likelihood ratio test in order to evaluate whether it is possible to use a single model to estimate height at each age (Table 3). The results show that the models differ statistically between ages ($p < 0.001$ in all cases). This suggests that the height growth of trees is strongly dependent on age and therefore it is not suitable to use a single equation for all ages.

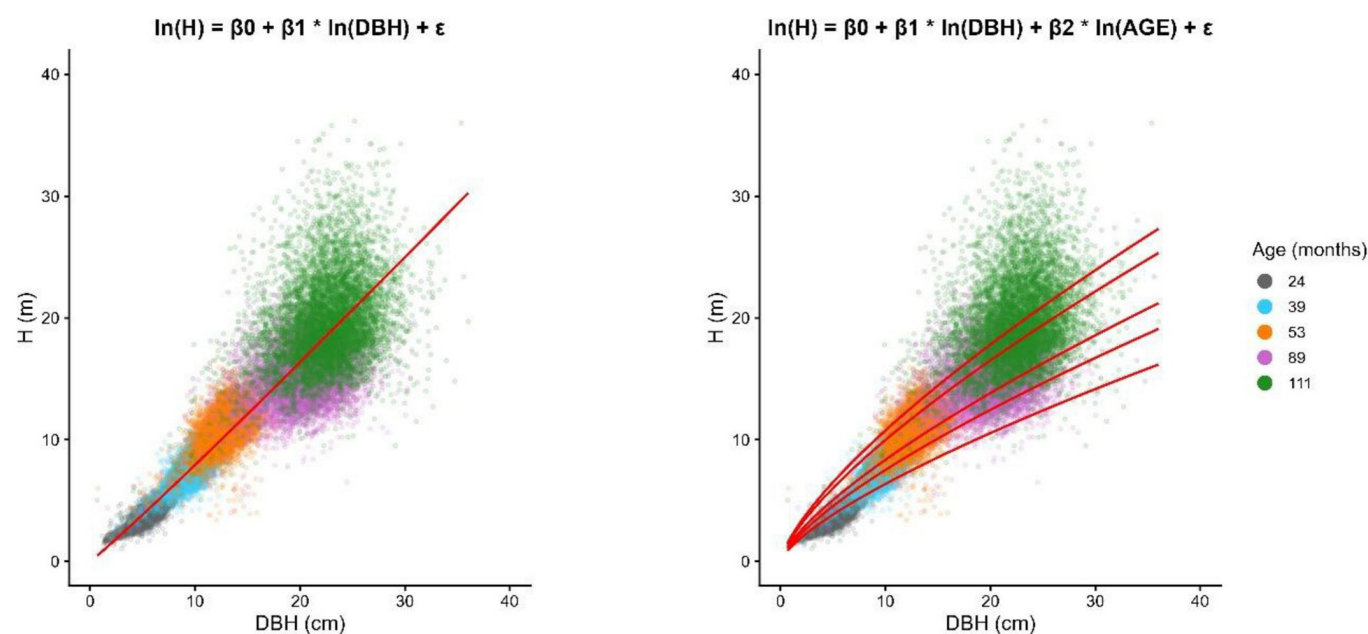


Figure 5: Scatter plot of height (H) as a function of diameter (DBH), considering the ages, in months (24, 39, 53, 89 and 111) of measurement, for the original model (considers DBH) and adapted (considers DBH and age).

Table 2: Estimated parameters and fit statistics of the hypsometric models adjusted by weighted least squares, separately by age, in the Analysis 2.

Model	Age (months)	β_0	β_1	β_2	R^2_{aj}	SEE	CV%
(1) $H = \beta_0 + \beta_1.DBH + \epsilon$	24	0.9175*	0.5270*	-	0.62	0.44	11.84
	39	1.0171*	0.6878*	-	0.53	0.89	11.45
	53	4.2844*	0.5140*	-	0.32	1.33	12.24
	89	10.0427*	0.2529*	-	0.11	2.21	14.59
	111	10.7442*	0.3899*	-	0.13	3.54	18.17
(2) $\ln H = \beta_0 + \beta_1.(1/DBH) + \epsilon$	24	1.8279*	-2.7067*	-	0.55	0.47	12.81
	39	2.7960*	-7.2918*	-	0.53	0.89	11.51
	53	2.5584*	-2.1646*	-	0.19	1.45	13.35
	89	3.0315*	-6.4064*	-	0.14	2.19	14.41
	111	3.3609*	-8.9273*	-	0.14	3.51	18.01
(3) $\ln H = \beta_0 + \beta_1.\ln DBH + \epsilon$	24	0.0637*	0.7461*	-	0.62	0.44	11.89
	39	0.0894*	0.8561*	-	0.53	0.89	11.43
	53	0.8178*	0.6127*	-	0.33	1.32	12.14
	89	1.7085*	0.3333*	-	0.13	2.20	14.50
	111	1.5710*	0.4457*	-	0.13	3.53	18.09
(4) $H = \beta_0 + \beta_1.DBH + \beta_2.DBH^2 + \epsilon$	24	3.6629*	0.5488*	0.0164*	0.62	0.44	11.84
	39	7.7961*	0.6560*	-0.0146*	0.53	0.89	11.42
	53	10.9970*	0.4874*	-0.0441*	0.35	1.30	11.99
	89	15.3165*	0.2332*	-0.0158*	0.13	2.19	14.45
	111	19.7566*	0.3513*	-0.0225*	0.14	3.51	18.02

Where: (*) indicate significant results by the t-test with a p-value < 0.05.

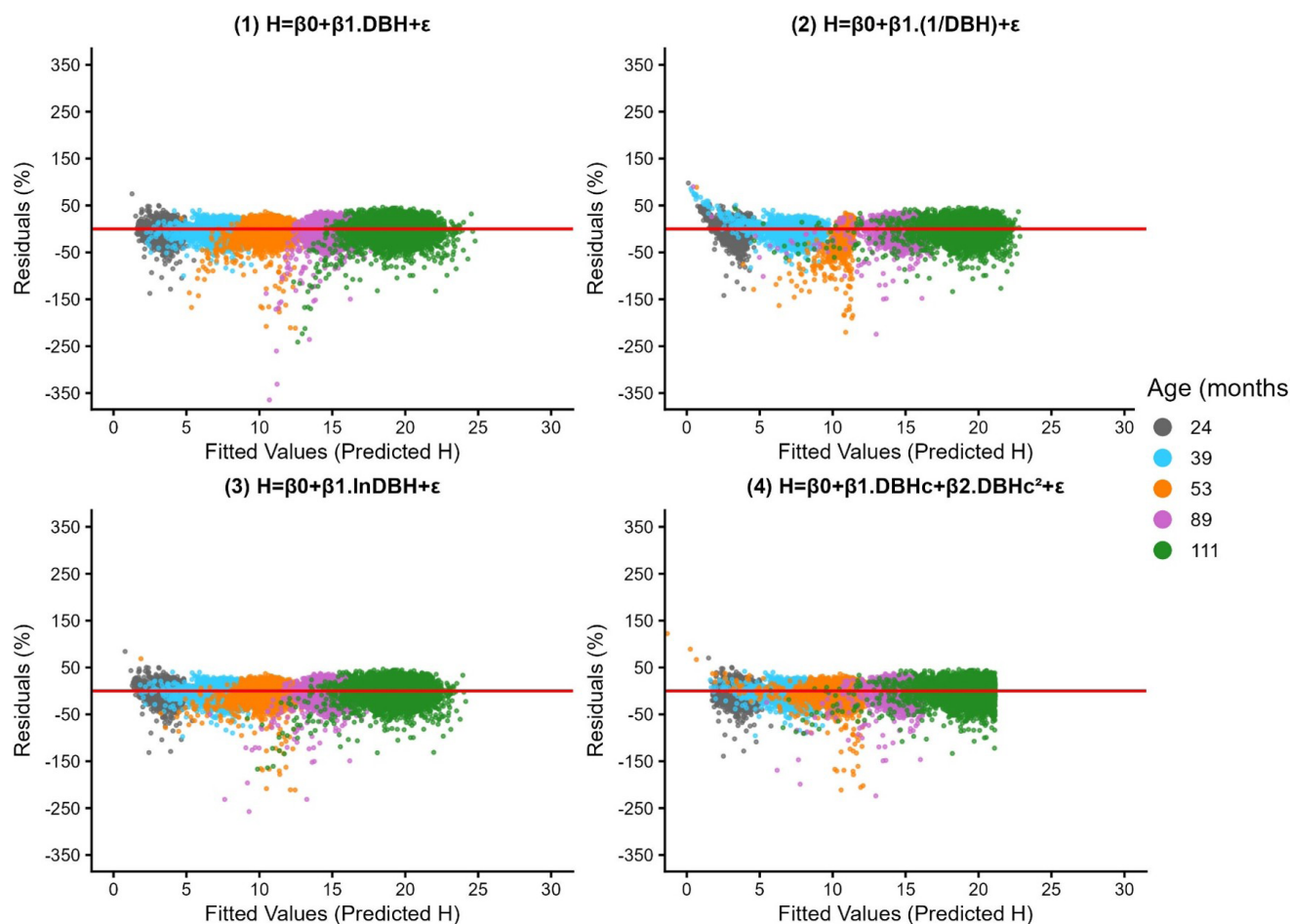
**Figure 6:** Graph of the dispersion of percentage residuals as a function of heights estimated by age-adjusted weighted hypsometric models in Analysis 2.

Table 3: Likelihood ratio test (LRT) model (3) $\ln H = \beta_0 + \beta_1 \ln DBH + \epsilon$, at different ages.

Model	Age (Months)	Log-Likelihood (LogLik)	Chi-Square (Chisq)	p-value
(3) $\ln H = \beta_0 + \beta_1 \ln DBH + \epsilon$	24	5315.5	-	-
	39	5554.6	3362.3	$< 2 \times 10^{-16} *$
	53	4821.7	2332.8	$< 2 \times 10^{-16} *$
	89	3850.8	752.3	$< 2 \times 10^{-16} *$
	111	2341.8	4531.7	$< 2 \times 10^{-16} *$

Where: (*) indicate significant results by the likelihood ratio test with a p-value < 0.05.

4. DISCUSSION

The results of the quality statistics considering Analysis 1 indicate that the inclusion of the age variable (adapted model) in the hypsometric models (original model) significantly improved the fit. This is an expected behavior, since the inclusion of other variables in the *DBH*, such as age, dominant height, site index, competition, stand density, among others, provide more accurate estimates of tree height than the exclusive use of the *DBH* (Hess et al., 2015; Mendonça et al., 2018; Hofiço et al., 2020; Gonçalves, 2022; Lafetá et al., 2023). However, it is necessary to know the effect of independent variables on the response variable (Dantas et al., 2024).

The 4.1 (original model) and 4.2 (adapted model) models showed greater accuracy in the height estimates according to the quality statistics, in relation to the models analyzed. However, the distribution of the residuals was considered problematic, being more evident when adding age (4.2). The fact is associated with the compression of the estimates of the higher heights, characteristic of the parabolic shape generated by the model, not capturing the actual biological growth of the trees. This means that the model establishes a decrease in the estimates as the diameter increases (Sanquetta et al., 2015; Nascimento et al., 2020).

The 3.2 model, which includes the age variable, showed better performance both in terms of biological realism and quality statistics, compared to the model that considers only the *DBH* (3.1), which is proven by the significance of the Graybill F test. The addition of age allowed for an increase in the accuracy of the model (3.2), and substantial improvements in the distribution of residuals, reducing trends in gaps and bias in the estimates (Sena et al., 2015).

Observing the prediction and accuracy statistics of the models adjusted for each age (Analysis 2), we identified a decrease in these with advancing age in all four models. Studies with the genus *Khaya* sp. in Mato Grosso do Sul, with the same spacing, at 36 months of age, resulted in values similar to those of the present study when considering younger ages (24 and 39) (Stolle et al., 2018). Studies show that linear models produce more accurate estimates of dendrometric variables for young stands, to the detriment of older stands (Santos et al., 2019; Rocha et al., 2025).

The drop in accuracy with advancing age can be explained by the aging of the trees, which reduces the increase in height relative to the diameter by flattening the hypsometric curve (Pelissari et al., 2014). This is a reflection of the slowdown in height growth, typical of mature trees, a characteristic that linear models cannot capture. Thus, hypsometric models adjusted for more developed *K. grandifoliola* stands tend to show a decrease in quality statistics.

Furthermore, genetic variability influences the hypsometric relationship (Mendonça et al., 2015). Therefore, silvicultural characteristics such as the seed origin of the *K. grandifoliola* stand, generate greater variability in the data and, therefore, greater error associated with height estimation at older ages.

Model 3, as in Analysis 1, presented a satisfactory performance for the height estimates for Analysis 2, considering the statistics of quality, waste distribution and biological realism. Even with a reduction in the precision of the estimates in the older age groups, (which was confirmed by the likelihood ratio test which indicated that the adjusted models using databases of different ages (24, 39, 53, 89 and 111 months)), there were statistically significant differences in the adjustments, evidencing the specificity of the hypsometric relationship by age. In line with these findings, recent evidence for planted forests indicates that the use of a single equation for height estimation under different planting conditions (age, species, thinning, stratum) does not result in accurate estimates (Murta Júnior et al., 2020; Carielo et al., 2022; Rocha et al., 2025).

However, the general model (Analysis 1), adjusted with the database that integrates all ages, showed superior performance ($R^2_{aj} = 0.86$), not only in comparison with the other general models, but also when compared to the age-adjusted models. This result is associated with the constitution of the database used; as general equations tend to benefit from larger samples for the accuracy of the estimates (Pearl, 2022; Rocha et al., 2025). In this context, despite the recommendation of specific equations for different ages, a single equation with the age variable can offer more accurate estimates of height in young stands of *K. grandifoliola*.

The variable performance between the models analyzed is due to their different mathematical nature. The choice of appropriate models capable of capturing the hypsometric curves of rapid growth for young trees and the reduction in growth as the age of the tree increases (Marziliano et al., 2019), combined with the identification of explanatory dendrometric variables, which contribute to the accuracy of the estimates, can reduce the number of adjusted equations (Alves et al., 2017).

5. CONCLUSIONS

Age influenced the hypsometric relationship of the young African mahogany stand. The inclusion of this variable in the models improved the height estimate, confirming that the use of diameter alone does not adequately represent the hypsometric variation when different ages are analyzed together.

Model 3.2 presented a better balance between statistical adjustment, residual distribution and biological realism, and is recommended for general estimates when there are data of different ages.

The age-adjusted models differed significantly from each other, indicating that an equation obtained at a specific age should not be applied indistinctly to the other phases of population development.

REFERENCES

- Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. D. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift (Berlin)*, 22(6), 711-728. <https://doi.org/10.1127/0941-2948/2013/0507>.

- Alves Júnior, J., Barbosa, L. H. A., Casaroli, D., Evangelista, A. W. P., & Costa, F. R. (2016). Crescimento de mogno africano submetido a diferentes níveis de irrigação por microaspersão. *Irriga*, 21(3), 466-466. <https://doi.org/10.15809/irriga.2016v21n3p466-480>.
- Alves, J. D. A., Calegario, N., Rosado, S. C. D. S., Silva, G. A., Possato, E. L., & Melo, E. D. A. (2017). Equações hipsométricas para *Toona ciliata* com inclusão de covariantes. *Ciência Florestal*, 27(2), 581-595. <https://doi.org/10.5902/1980509827738>.
- Azevedo, C. P., Muroya, K., Garcia, L. C., Lima, R. M. B., Moura, J. D., & Neves, E. J. M. (1999). Relação hipsométrica para quatro espécies florestais em plantio homogêneo e em diferentes idades na Amazônia ocidental. *Boletim de Pesquisa Florestal*, 39(1), 5-29.
- Breusch, T. S., & Pagan, A. R. (1979). A simple test for heteroscedasticity and random coefficient variation. *Econometrica*, 47(5), 1287-1294. <https://doi.org/10.2307/1911963>.
- Carielo, P., Arce, J. E., Figueiredo Filho, A., Pelissari, A. L., Kohler, S. V., Retslaff, F. A. D. S., & Behling, A. (2022). Agrupamento de dados para ajustes de modelos hipsométricos e volumétricos em povoamentos de *Pinus oocarpa* e *Pinus caribaea* var. *hondurensis*. *Ciência Florestal*, 32(3), 1165-1186. <https://doi.org/10.5902/1980509835017>.
- Dalal, D. K., & Zickar, M. J. (2012). Some common myths about centering predictor variables in moderated multiple regression and polynomial regression. *Organizational Research Methods*, 15(3), 339-362. <https://doi.org/10.1177/1094428111430540>.
- Dantas, D., Pinto, L. O. R., Lacerda, T. H. S., Cordeiro, N. G., & Calegario, N. (2024). Accuracy of tree height estimation with model extracted from artificial neural network and new linear and nonlinear models. *Acta Scientiarum. Agronomy*, 46(1), e63286. <https://doi.org/10.4025/actasciagron.v46i1.63286>.
- Fox, J., & Weisberg, S. (2019). *An R Companion to Applied Regression* (3rd ed.). Thousand Oaks, CA: Sage.
- Gonçalves, A. C. (2022). Stand structure impacts on forest modelling. *Applied Sciences (Basel, Switzerland)*, 12(14), 6963. <https://doi.org/10.3390/app12146963>.
- Gonçalves, K. D. S., Sousa, H. R. S., Cinque Mariano, D., Augusto Ebling, Â., Oliveira Neto, C. F., & Shigueru Okumura, R. (2023). Qualidade de povoamentos de Mogno africano na Amazônia Oriental. *Revista em Agronegócio e Meio Ambiente*, 16(3), 1-17. <https://doi.org/10.17765/2176-9168.2023v16n3e10030>.
- Graybill, J. (1976). *Theory and application of the linear model*. Belmont: Duxbury.
- Gregoire, T. G., & Dyer, M. E. (1989). Model fitting under patterned heterogeneity of variance. *Forest Science*, 35(1), 105-125. <https://doi.org/10.1093/forestscience/35.1.105>.
- Gujarati, D. N., & Porter, D. C. (2011). *Econometria Básica* (5. ed., 920 p). Porto Alegre: Bookman.
- Hess, A. F., Cianorschi, L., Silvestre, R., Scariot, R., & Ricken, P. (2015). Aplicação dos modelos lineares generalizados para estimativa do crescimento em altura. *Pesquisa Florestal Brasileira*, 35(84), 427-433. <https://doi.org/10.4336/2015.pfb.35.84.604>.
- Hofico, N. D. S. A., Costa, E. A., Fleig, F. D., Finger, C. A. G., & Hess, A. F. (2020). Height-diameter relationships for *Eucalyptus grandis* Hill Ex. Maiden in Mozambique: using mixed-effects modeling approach. *Cerne*, 26(2), 183-192. <https://doi.org/10.1590/01047760202026022677>.
- Lacobucci, D., Schneider, M. J., Popovich, D. L., & Bakamitsos, G. A. (2016). Mean centering helps alleviate “micro” but not “macro” multicollinearity. *Behavior Research Methods*, 48(4), 1308-1317. PMID:26148824. <https://doi.org/10.3758/s13428-015-0624-x>.
- Lafetá, B. O., Pimenta, I. A., Santos, M. A. D., Brenda, H., Rodrigues, X., Fontan, I. D. C. I., Ferraro, A. C., & Vieira, D. D. S. (2023). Alternativas de modelagem para a estimativa da altura de árvores de eucalipto. *Revista Forestal Mesoamericana Kurú*, 20(47), 1-8. <https://doi.org/10.18845/rfmk.v20i47.6816>.
- Machado, S. A., & Figueiredo Filho, A. (2003). *Dendrometria*. Curitiba: Embrapa.
- Marziliano, P. A., Tognetti, R., & Lombardi, F. (2019). Is tree age or tree size reducing height increment in *Abies alba* Mill. at its southernmost distribution limit? *Annals of Forest Science*, 76(1), 17. <https://doi.org/10.1007/s13595-019-0803-5>.
- Matias, R. K., Brito, C. N., Resende, R. T., Rios, J. M., Santana, G. M., De Oliveira, G. M., & Venturoli, F. (2023). Biometric assessment of early stem growth at a commercial stand of African mahogany (*Khaya grandifoliola*). *Bioscience Journal*, 39, e39002. <https://doi.org/10.14393/BJ-v39n0a2023-62994>.
- Mendonça, A. R. D., Carvalho, S. D. P. C. E., & Calegario, N. (2015). Modelos hipsométricos generalizados mistos na predição da altura de *Eucalyptus* sp. *Cerne*, 21(1), 107-115. <https://doi.org/10.1590/01047760201521011191>.
- Mendonça, A. R., da Silva, J. C., Aozai, T. S., da Silva, E. R., Santos, J. S., Binoti, D. H. B., & da Silva, G. F. (2018). Estimação da altura total de árvores de ipê felpudo utilizando modelos de regressão e redes neurais. *Brazilian Journal of Biometrics*, 36(1), 128-139.
- Meyer, H. A. (1941). A correction for a systematic error occurring in the application of the logarithmic volume equation. *Pennsylvania State Forest School*.
- Midway, S., & White, J. W. (2025). Testing for normality in regression models: mistakes abound (but may not matter). *Royal Society Open Science*, 12(4), 241904. PMID:40309180. <https://doi.org/10.1098/rsos.241904>.
- Miranda, R. O. V., Zarpelon, F. D. A., Kohler, S. V., Soares, A. A. V., Miranda, I. D. S., & Kuchla, W. C. (2022). Precision and accuracy of sampling methods in thinned *Pinus taeda* L. stands. *Floresta*, 52(1), 45-53. <https://doi.org/10.5380/rf.v52i1.74285>.
- Murta Júnior, L. S., Castro, R. V. O., Nappo, M., Nogueira, G. S., Araújo Júnior, C. A., Oliveira Gaspar, R., & da Costa, L. S. (2020). Características dendrométricas de eucalipto submetido a desbaste. *Scientia Forestalis*, 48(127), e2948. <https://doi.org/10.18671/scifor.v48n127.22>.
- Nakajima, N. Y., Netto, S. P., Druszczyk, J. P., & Junior, M. Y. (2011). Comparação da precisão entre os métodos de amostragem linha e parcela circular concêntrica em povoamentos de *Pinus elliottii*. *Revista Acadêmica (Pontifícia Universidade Católica do Paraná)*, 9(2), 131-139. <https://doi.org/10.7213/cienciaanimal.v9i2.11750>.
- Nascimento, R. G. M., Vanclay, J. K., Figueiredo Filho, A., do Amaral Machado, S., Ruschel, A. R., Hiramatsu, N. A., & de Freitas, L. J. M. (2020). The tree height estimated by non-power models on volumetric models provides reliable predictions of wood volume: the Amazon species height modelling issue. *Trees, Forests and People*, 2, 100028. <https://doi.org/10.1016/j.tfp.2020.100028>.
- Pearl, J. (2022). Comment: understanding Simpson's paradox. In H. Geffner, R. Dechter & J. Y. Halpern (Eds.), *Probabilistic and causal inference: the works of judea pearl* (pp. 399-412). New York: ACM. <https://doi.org/10.1145/3501714.3501738>.
- Pelissari, A. L., Figueiredo Filho, A., Caldeira, S. F., & Machado, S. A. (2014). Geostatistic applied to spatial modeling of hypsometric relationships in forest stands. *American International Journal of Contemporary Research*, 4(7), 67-76.
- R Core Team. (2025). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: Foundation for Statistical Computing.
- Ribeiro, A., Ferraz Filho, A. C., & Scolforo, J. R. S. (2017). O cultivo do mogno africano (*Khaya* spp.) e o crescimento da atividade no Brasil. *Floresta e Ambiente*, 24(0), e00076814. <https://doi.org/10.1590/2179-8087.076814>.
- Ribeiro, A., Ferraz-Filho, A. C., & Soares-Scolforo, J. R. (2018). Predicción de la altura en plantaciones brasileñas de *Khaya ivorensis*. *Bosque (Valdivia)*, 39(1), 15-26. <https://doi.org/10.4067/S0717-92002018000100015>.

- Rocha, Q. S., Muribeca, P. F., Veras, B. F., Maciel, R. P., Bufalino, L., & Nascimento, R. G. M. (2025). Hypsometric relationship of *Schizolobium parahybavar. amazonicum* in plantations integrated with livestock in eastern Amazonia: applications of different modeling methods. *Cerne*, 31, e-103502. <https://doi.org/10.1590/01047760202531013502>.
- Rodriguez, L. C. E., Polizel, J. L., Ferraz, S. F., Zonete, M. F., & Ferreira, M. Z. (2010). Inventário florestal com tecnologia *laser* aerotransportada de plantios de *Eucalyptus* spp no Brasil. *Revista Ambienta*., 6, 67-80.
- Sanquetta, M. N. I., Sanquetta, C. R., Mognon, F., Dalla Corte, A. P., Rodrigues, A. L., & Maas, G. C. B. (2015). Ajuste de equações hipsométricas para a estimação da altura total de indivíduos jovens de teca. *Científica (Jaboticabal)*, 43(4), 400-406. <https://doi.org/10.15361/1984-5529.2015v43n4p400-406>.
- Santos, F. M., Terra, G., Chaer, G. M., & Monte, M. A. (2019). Modeling the height-diameter relationship and volume of young African mahoganies established in successional agroforestry systems in northeastern Brazil. *New Forests*, 50(3), 389-407. <https://doi.org/10.1007/s11056-018-9665-1>.
- Schneider, P. R., Schneider, P. S. P., & Souza, C. A. M. (2009). *Análise de regressão aplicada à Engenharia Florestal*. Santa Maria. Universidade Federal de Santa Maria.
- Sena, A. L. M., Silva Neto, A. J., Oliveira, G. M. V., & Calegario, N. (2015). Modelos lineares e não lineares com uso de covariantes para relação hipsométrica de duas espécies de *Pinus* tropicais. *Ciência Florestal*, 25(4), 969-981. <https://doi.org/10.5902/1980509820651>.
- Sérvulo, A. C., Vellame, L. M., Casaroli, D., Alves Júnior, J., & Souza, P. H. D. (2017). African Mahogany transpiration with Granier method and water table lysimeter. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 21(5), 322-326. <https://doi.org/10.1590/1807-1929/agriambi.v21n5p322-326>.
- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52(3-4), 591-611. <https://doi.org/10.1093/biomet/52.3-4.591>.
- Stolle, L., Velozo, D. R., Dalla Corte, A. P., Sanquetta, R. C., & Beutling, A. (2018). Modelos Hipsométricos para um povoamento jovem de *Khaya ivorensis* a. chev. *BIOFIX Scientific Journal*, 3(2), 231-236. <https://doi.org/10.5380/biofix.v3i2.58799>.
- Velten, K., Schmidt, D. M., & Kahlen, K. (2024). *Mathematical modeling and simulation: introduction for scientists and engineers*. Germany: Wiley. <https://doi.org/10.1002/9783527849604>.
- White, H. (1980). A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica*, 48(4), 817-838. <https://doi.org/10.2307/1912934>.
- Zeileis, A., & Hothorn, T. (2002). Diagnostic checking in regression relationships. *R News*, 3(2), 7-10.

AUTHOR CONTRIBUTIONS

JFC: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft, writing – review & editing; AFS: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft; FBRF: conceptualization, investigation, visualization, writing – review & editing; LGSS: conceptualization, investigation, visualization, writing – review & editing; GSCL: conceptualization, investigation, visualization, writing – review & editing; EBG: funding acquisition, resources, visualization; GSN: funding acquisition, resources, visualization; MLRO: formal analysis; funding acquisition, resources, visualization, writing – review & editing; RVOC: formal analysis, funding acquisition, project administration, resources, visualization, writing – review & editing.