DOI: 10.5965/223811712332024492

Revista de Ciências Agroveterinárias 23 (3): 2024
Universidade do Estado de Santa Catarina

Applications of hypsometric relations and volumetry in seminal stand of *Eucalyptus cloeziana* F. Muell.

Aplicações de relações hipsométricas e volumetria em povoamento seminal de Eucalyptus cloeziana F. Muell.

Bruno Oliveira Lafetá [1(ORCID 0000-0003-2913-6617)], João Marcos Barbosa Sampaio [1(ORCID 0000-0002-6796-5910)], Vitor Augusto Cordeiro Milagres [2(ORCID 0000-0002-9540-9217)], Ivan da Costa Ilhéu Fontan [1(ORCID 0000-0003-4143-5433)], Diego dos Santos Vieira [3(ORCID 0000-0003-3780-1189)], Erik Brian dos Santos [1(ORCID 0009-0002-0458-6902)]

[1]Federal Institute of Education, Science and Technology of Minas Gerais, São João Evangelista, MG, Brazil. *Author for correspondence: bruno.lafeta@ifmg.edu.br
[2]Santa Maria Agroforestry Innovations, Anápolis, GO, Brazil.
[3]Federal University of Vales do Jequitinhonha e Mucuri, Diamantina, MG, Brazil.

Submission: 28/12/2023 | Accepted: 07/05/2024

RESUMO

Investigações científicas sobre a aplicação de relações hipsométricas fornecem subsídios importantes para a quantificação de recursos madeireiros e manejo florestal. Assim, a pesquisa objetivou avaliar alternativas para a modelagem e uso de relações hipsométricas em um povoamento seminal de *Eucalyptus cloeziana* F. Muell., localizado no município de Minas Novas, Minas Gerais. O inventário florestal foi realizado aos 60 meses de idade e consistiu na distribuição aleatória de 10 unidades amostrais. Foram testados os seguintes métodos de modelagem hipsométrica: regressão linear, regressão não linear e máquinas vetor de suporte (MVS). Avaliaram-se duas abordagens para a aplicação de relações hipsométricas empregando diferentes métodos de modelagem: P1) estimativa da altura de todos os fustes inventariados (alturas estimadas) e; P2) estimativa de altura apenas daqueles indivíduos que tiveram somente o DAP mensurado (combinação de alturas medidas e estimadas). A informações biométricas obtidas foram submetidas à análise estatística descritiva e teste t não pareado. As relações hipsométricas dos ajustes dos modelos de Curtis (regressão linear), Logístico (regressão não linear) e MVS com função Kernel de base radial exibiram as melhores qualidades preditivas. Em termos médios, os volumes calculados não se diferenciam estatisticamente entre as abordagens P1 e P2. Conclui-se que a abordagem P1 é uma alternativa para a aplicação de relações hipsométricas apropriadamente estabelecidas e não compromete a quantificação volumétrica florestal. A variabilidade biométrica tende a ser menor com a estimativa da altura de todos os fustes inventariados.

PALAVRAS-CHAVE: altura; regressão; inteligência artificial.

ABSTRACT

Scientific investigations on the application of hypsometric relationships provide important support for quantification of wood resources and forest management. Thus, this research aimed to evaluate alternatives for the modeling and use of hypsometric relationships in seminal stand of *Eucalyptus cloeziana* F. Muell., located in the municipality of Minas Novas, Minas Gerais. Forest inventory was carried out at 60 months of age and consisted random distribution of 10 sampling units. The following hypsometric modeling methods were tested: linear regression, nonlinear regression, and support vector machines (MVS). Two approaches for applying hypsometric relationships were evaluated using different modeling methods: P1) height estimate of all inventoried of all inventoried stems (estimated heights) and; P2) height estimate of only those individuals who had only DBH measured (combination of measured and estimated heights). Biometric information obtained was subjected to descriptive statistical analysis and unpaired t-test. Hypsometric relationships of the models fits of Curtis (linear regression), Logistic (non-linear regression) and support vector machines with radial basis Kernel function exhibited the best predictive qualities. On average, calculated volumes do not differ statistically between approaches P1 and P2. It is concluded that P1 approach is an alternative for application of properly established hypsometric relationships and does not compromise forest volumetric quantification. Biometric variability tends to be smaller with the estimation of the height of all inventoried stems.

KEYWORDS: height; regression; artificial intelligence.

INTRODUCTION

The Brazilian forestry sector is experiencing robust competitive growth in the global market, with over 7.5 million hectares of eucalyptus plantations, achieving an average productivity of approximately 32.7 $m^3ha^{-1}year^{-1}$ (IBÁ 2023). Forest mensuration plays a crucial role in quantifying productivity, providing essential data for the rational planning and management of timber resources (CAMPOS & LEITE 2017, LAFETÁ et al. 2021). Accurate biometric information allows for more assertive decision-making and better management of the production chain.

Forest inventories in even-aged stands typically involve measuring the diameter of all stems within sample plots while recording the height of only a subset of the inventoried stems. This approach is warranted due to the challenges associated with height measurement, which is often costly, labor-intensive, and prone to various non-sampling errors. These errors can be exacerbated by adverse weather conditions, such as strong winds, or visual obstructions faced by operators, including terrain slopes, understory vegetation, or overlapping canopies (SHARMA et al. 2019, BUENO & COSTA 2020, DANTAS et al. 2020, SOARES et al. 2021). Biometric modeling emerges as an alternative for estimating stem height, and despite extensive research, questions persist regarding strategies that can be adopted following the establishment of height-diameter relationships.

Hypsometric relationships, symbolized by h/d, are defined by establishing functions for estimating individual stem height on the basis of a predictor variable that is easier and quicker to measure, diameter (SANQUETTA et al. 2015, MIGUEL et al. 2018). The utilization of these relationships streamlines field data collection, enhancing the efficiency, cost-effectiveness, and accuracy of forest inventories. 2018, NICOLETTI et al. 2020, TÉO & SILVA 2020, SOARES et al. 2021). In contrast, these relationships do not always exhibit a well-defined biological association, potentially showing significant height variability for a given diameter (MARTINS et al. 2021).

Selecting an appropriate method for modeling height-diameter relationships can be challenging due to nonlinear relationships between biometric attributes and inherent biological constraints of statistical model parameters (MARTINS et al.). 2021). Linear regression is the most widely used statistical method in height-diameter modeling due to its ease of fitting, interpretation, and application of equations. Forest literature encompasses several traditional models, including those developed by TROREY (1932), HENRICKSEN (1950), STOFFELS & SOEST (1953), and the widely used CURTIS (1967).

Advancements in computational resources have facilitated the application of nonlinear regression and artificial intelligence in height-diameter modeling. Sigmoidal nonlinear regression models are widely employed due to their biological foundation, facilitating rapid reliability analysis of estimates regarding the convergence of the parameterization algorithm. On the other hand, Support Vector Machines (SVM), developed by VAPNIK (1995), represent a supervised learning-based artificial intelligence approach for addressing complex pattern classification, regression, and outlier detection problems (KUMAR et al. 2019)

It is worth noting that approaches to applying height-diameter relationships are subject to debate, particularly regarding their implications for volumetric estimates (BATISTA et 2014). The approaches to using hypsometric relationships can basically be divided into two categories: the first is based on estimating the height of all the inventoried stems and the second, which is often carried out, involves estimating height only for those that have only had their diameter measured (SCOLFORO et al. 2015, MARTINS et al. 2021, DANTAS et al. 2020, SOARES et al. 2021). This final category yields a hypsometric vector that combines estimated heights with field measurements.

Given the above, this study aimed to evaluate alternatives for modeling and using height-diameter relationships in a seedling stand of *Eucalyptus cloeziana* F. Muell. located in Minas Novas, Minas Gerais.

MATERIAL AND METHODS

The work was carried out in an E. *cloeziana* seed management unit in the municipality of Minas Novas-MG, at UTM (Universal Transverse Mercator) coordinates 778.263m E and 8.077.359 N (Sirgas 2000 Datum, Zone 23S). The region's climate is classified as "Aw" according to Köppen (KÖPPEN 1936) characterized by a tropical savanna climate with distinct wet and dry seasons. According to climatological norms from the National Institute of Meteorology (INMET 2024), annual averages for temperature and precipitation are 23°C (ranging from 20°C in June and July to 25°C in February and October) and 960 mm (ranging from 2 mm in June and August to 199 mm in December), respectively.

The seed orchard was established in December 2015 using a 6.00 × 1.25 m spatial arrangement, covering a total area of 33.04 ha. The forest inventory was conducted at 60 months of age, with 10 rectangular plots of 552 m^2 (18.4 × 30.0 m) randomly distributed on flat terrain (sampling intensity of 1.67%). Diameter at breast height (DBH, measured at 1.30 m above ground level) of all stems was recorded using a mechanical caliper, while total height (H) of the first 10 stems was measured using a Haglof electronic hypsometer.

Three hypsometric modeling approaches were evaluated using DBH as the sole predictor variable: linear regression, nonlinear regression, and SVM. Linear and nonlinear regression analyses were conducted using Ordinary Least Squares (OLS) and the Levenberg-Marquardt iterative method, respectively. The tested height-diameter models are shown in Table 1.

Table 1. Hypsometric models tested for height estimation in a seminal stand of E. *cloeziana* at 60 months of age.

Identification	Hypsometric models	Author(s)
	--------------------------- Linear ---------------------------	
(1)	$H = \beta_0 + \beta_1.DAP + \varepsilon$	Simple linear
(2)	$H = \beta_0 + \beta_1.DAP + \beta_2.DAP^2 + \varepsilon$	TROREY (1932)
(3)	$H = \beta_0 + \beta_1.Ln(DAP) + \varepsilon$	HENRICKSEN (1950)
(4)	$Ln(H) = \beta_0 + \beta_1.Ln(DAP) + \varepsilon$	STOFFELS AND SOEST (1953)
(5)	$Ln(H) = \beta_0 + \beta_1.(1/DAP) + \varepsilon$	CURTIS (1967)
	------------------------- Non-linear -------------------------	
(6)	$H = \frac{\beta_0}{1 + \beta_1 e^{-\beta_2 DAP}} + \varepsilon$	Logistics
(7)	$H = \beta_0 e^{-e^{\beta_1 - \beta_2 DAP}} + \varepsilon$	GOMPERTZ (1825)

H = total height; DBH = diameter at breast height with bark; Nl = natural logarithm; β_0, β_1, and β_2 = regression coefficients; and ε = random error.

The assumptions of the OLS method were assessed, including residual normality using the Shapiro-Wilk test and homoscedasticity using the Breusch-Pagan test. To assess multicollinearity in the TROREY (1932) model, the Variance Inflation Factor (VIF) was calculated.

The development of support vector machines was grounded in statistical learning theory, as elaborated by VAPNIK (1995) and MEYER et al. (2023). The VMS were implemented using the R package "e1071" (MEYER et al. 2023) with a cost parameter of 2, a gamma of 0.1 and an epsilon of 1; parameters defined by exploratory analysis, with values ranging from 0.001 to 10. For SVM parameterization, four types of Kernel functions were evaluated: linear, radial basis, sigmoid, and polynomial.

Hypsometric models were evaluated based on parameter significance using t-tests, Mean Absolute Deviation (MAD), Root Mean Square Error (RMSE), and linear correlation coefficient (r) between observed and estimated values. Graphical analyses involved statistical inspection of residual dispersion and observed values compared to estimated ones. Data points deviating from the general trend were retained in statistical analyses to assess model predictive power in the presence of potential outliers or noise.

Two approaches for applying hypsometric relationships were compared: one based on estimating the height of all inventoried stems (P1, estimated heights) and another focused on estimating the height of individuals with only DBH measurements (P2, combining measured and estimated heights). The individual stem volume with bark (V, m^3 ind^{-1}) was calculated using an equation provided by the forestry company (adjusted coefficient of determination of 0.99), derived from fitting Spurr's model (SPURR 1962):

$$Ln(V) = -10{,}413796 + 1{,}032427\ Ln(DAP\ H^2)$$

Hypsometric and volumetric data were visualized using boxplots and analyzed through descriptive statistics, including mean, median, coefficient of variation, kurtosis, and skewness (calculated using the method of moments). An unpaired t-test was conducted to compare the two approaches for applying height-diameter relationships. Statistical significance was assessed at the 1% and 5% levels for all analyses. These were carried out using the R software version 4.1.3 (R CORE TEAM 2022).

RESULTS AND DISCUSSION

The assumptions of residual normality and homoscedasticity were met ($p > 0.05$) for all linear regressions, as verified by the Shapiro-Wilk and Breusch-Pagan tests, respectively. The inflation factor of the variance in the fitted TROREY (1932) model was 76, indicating multicollinearity. Table 2 presents the coefficients and goodness-of-fit metrics for the tested linear and nonlinear height-diameter models. All equation coefficients were significant ($p \leq 0.05$), except for those derived from the TROREY (1932), HENRICKSEN (1950), and GOMPERTZ (1825) models. These three equations were discarded from subsequent graphical analyses. In general, the equations exhibited minimal deviations (low RMSE and MAD values) and Pearson correlations exceeding 0.76. The equations derived from CURTIS's (1967) linear model and the nonlinear logistic model demonstrated superior fit quality. As expected, the asymptote of this model, represented by the parameter "β_0" was positive.

Table 2. Coefficients and fit quality of hypsometric models for stems contained in a seminal stand of E. *cloeziana* at 60 months of age.

Id.	β_0	β_1	β_2	MAD	RMSE	r
		------------------------ Linear regressions ------------------------				
(1)	10,803598**	0,522157**	-	0,7937	0,9818	0,7388**
(2)	2,632411^{ns}	1,980541**	-0,062712**	0,7375	0,9181	0,7764**
(3)	2,291767^{ns}	5,990708**	-	0,7608	0,9452	0,7609**
(4)	1,922618**	0,368971**	-	0,7707	0,9572	0,7543**
(5)	3,173857**	-3,929461**	-	0,7467	0,9341	0,7676**
		--------------------- Non-linear regressions ---------------------				
(6)	19,221815**	2,809407*	0,270025**	0,7426	0,9254	0,7723**
(7)	19,441822**	0,587214^{ns}	0,228251**	0,7438	0,9272	0,7713**

*, ** significant at the 99 and 95% probability level by the t-test; ^{ns} not significant at the 95% probability level by the t-test; MAD = mean of the absolute deviations; RMSE = square root of the mean error and; r = correlation coefficient.

Among the kernel functions, radial basis support vector machines demonstrated superior parameterization quality and performance for estimating E. *cloeziana* stem heights, while also offering greater simplicity due to their reduced number of vectors (Table 3). In general, the percentage residuals of the hypsometric modeling methods visually approximated a homoscedastic distribution, except when vector machines with a Polynomial function were employed (Figure 1). The residuals were closer to the abscissa axis in the equations derived from fitting the CURTIS (1967; linear regression), Logistic (non-linear regression), and SVM with radial basis function Kernel models. Consequently, these models were selected for generating height-diameter curves and their respective application.

The hypsometric relationships selected for each modeling method are illustrated in Figure 2. The classic sigmoidal, S-shaped behavior was most pronounced in the hypsometric curve when using SVM with a radial basis function kernel, characterized by an initial phase of slow height growth relative to diameter, followed by an intensification and subsequent reduction in growth rate.

Table 3. Statistics of approximations by support vector machines constructed for the estimation of stem height in a seminal stand of E. *cloeziana* at 60 months of age.

Kernel function	Number of vectors	MAD	RMSE	r
Radial	14	0,7426	0,9254	0,7723**
Sigmoidal	19	0,7689	0,9411	0,7755**
Polynomial	25	0,8179	1,0110	0,7246**
Linear	19	0,9421	1,1802	0,6487**

** significant at the 99% probability confidence level using the t-test. MAD = mean of the absolute deviations; RMSE = square root of the mean error and; r = correlation coefficient.

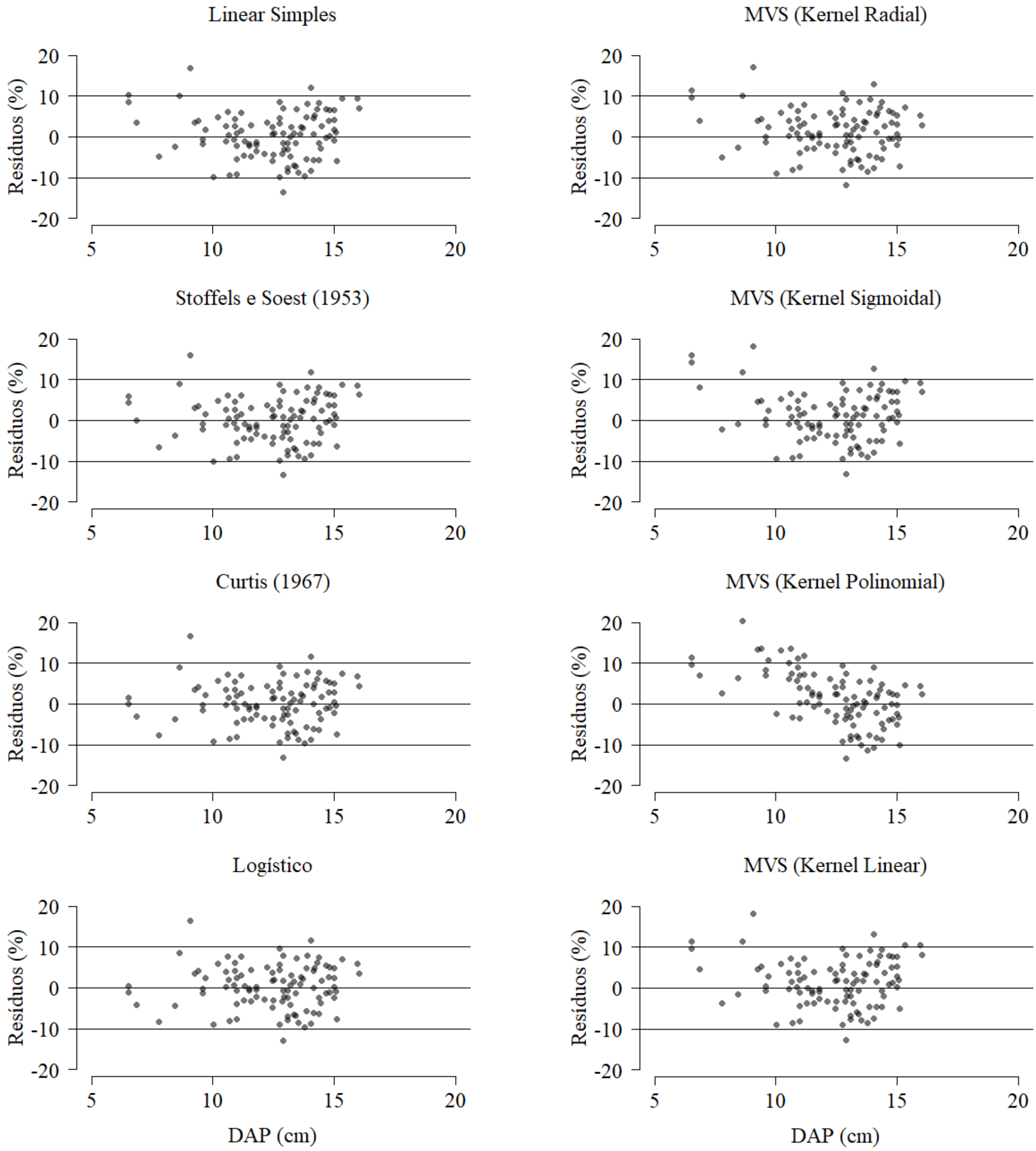

Figure 1. Distribution of percentage residues of height (m) and volume (m^3 $ind.^{-1}$) of E. *cloeziana* for different hypsometric modeling methods. SVM = support vector machines.

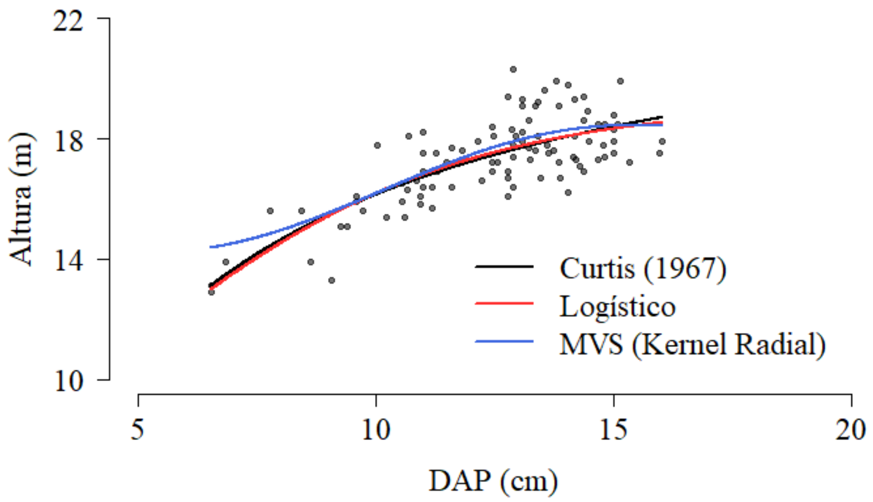

Figure 2. Curves of the hypsometric equations generated for a seminal E. *cloeziana* stand at 60 months of age. SVM = support vector machines.

Regarding stem height and individual volume, the means did not differ significantly ($p > 0.05$) between the two approaches for applying the height-diameter relationship. On the other hand, the coefficients of variation for height and volume associated with the P2 approach tended to be slightly higher than those of P1 across all modeling methods (Table 4). This finding is corroborated by the data dispersion illustrated in the boxplot, where the range between the lower and upper limits (calculated using interquartile range information) was narrower when applying the P1 approach to estimate the height of all inventoried stems (Figure 3). The distribution exhibited leptokurtic characteristics and negative skewness across all evaluated approaches. According to the unpaired t-test, individual height and volume data did not significantly differ between approaches for applying the height-diameter relationship ($p > 0.05$).

Table 4. Descriptive statistics of height (m) and volume (m^3 $ind.^{-1}$) for a seminal E. *cloeziana* stand at 60 months of age, employing different modeling methods and approaches for the application of hypsometric relationships.

Approach	Hypsometric ratio	Mean	Median	VC (%)	Kurtosis	Asymmetry
			-------------------- Height --------------------			
P1	CURTIS (1967)	17,2573	17,5735	6,7053	5,0455	-1,4238
	Logistics	17,2738	17,6492	6,7373	5,5696	-1,6205
	VMS (Kernel Radial)	17,4364	17,8435	6,1835	3,3869	-1,1799
P2	CURTIS (1967)	17,2607	17,5667	6,9974	4,7155	-1,2134
	Logistics	17,2738	17,6430	7,0222	5,0853	-1,3677
	VMS (Kernel Radial)	17,4128	17,8363	6,5776	3,7157	-1,0677
			-------------------- Volume --------------------			
P1	CURTIS (1967)	0,1092	0,1115	37,7360	2,4300	-0,1299
	Logistics	0,1093	0,1120	37,4897	2,4077	-0,1709
	VMS (Kernel Radial)	0,1102	0,1133	37,2528	2,2933	-0,2008
P2	CURTIS (1967)	0,1093	0,1115	37,7310	2,4213	-0,1382
	Logistics	0,1093	0,1120	37,5127	2,3974	-0,1754
	VMS (Kernel Radial)	0,1101	0,1130	37,2994	2,2941	-0,2032

P1 = estimated height of all inventoried stems (estimated heights); P2 = height estimate only for individuals with measured DBH (P2, combination of measured and estimated heights); CV = coefficient of variation; SVM = support vector machines.

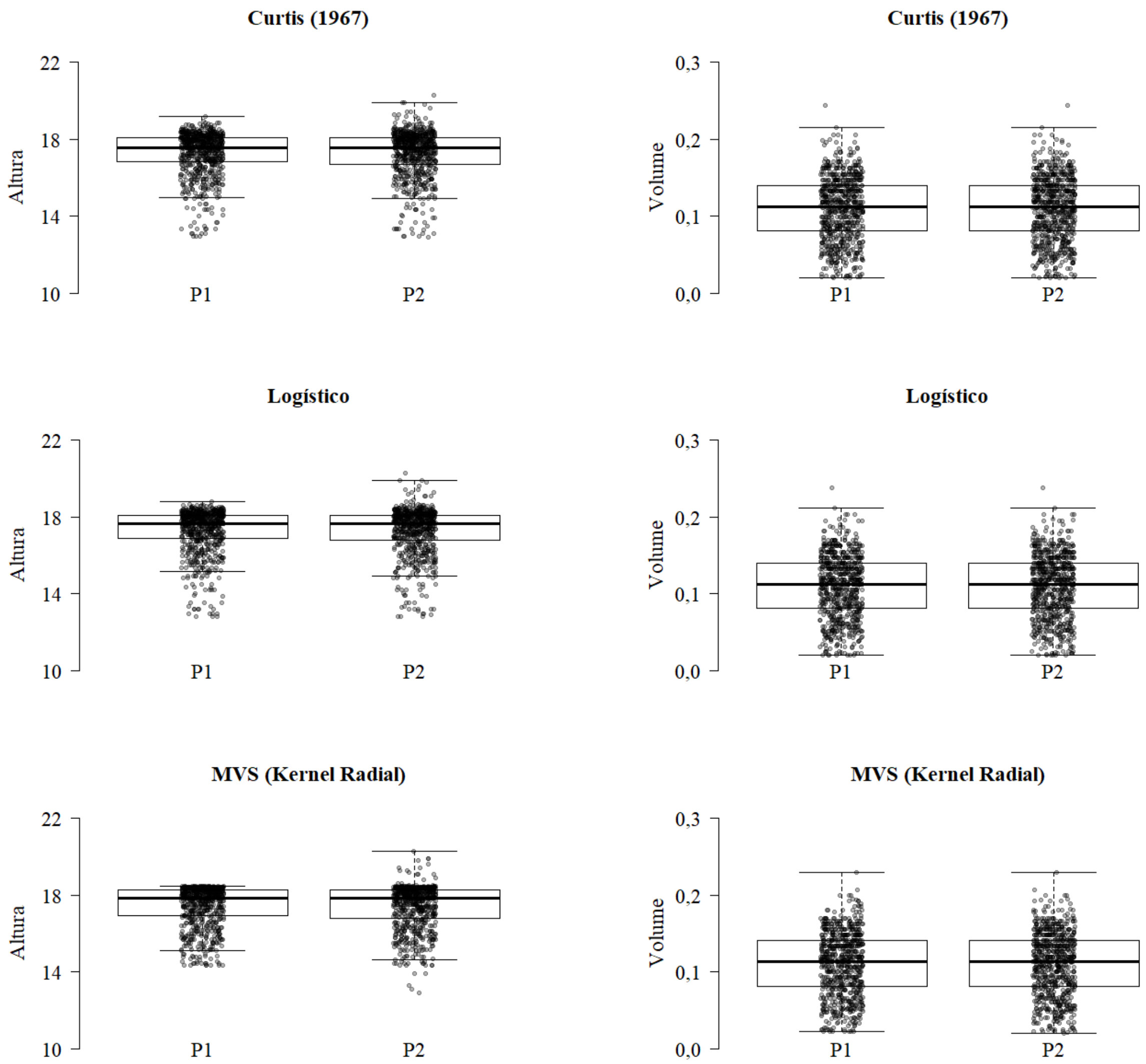

Figure 3. Boxplot of height (m) and volume (m^3 $ind.^{-1}$) of E. *cloeziana* employing different modeling methods and approaches for the application of hypsometric relationships. SVM = support vector machines. P1 = estimate of height for all inventoried stems (estimated heights). P2 = height estimate only for those individuals that had only DBH measured (P2, combination of measured and estimated heights).

The volumetric estimates of the E. *cloeziana* stand at 60 months of age, calculated using linear (CURTIS 1967) and non-linear (Logistic) regressions, were similar across procedures for height-diameter relationship, approximately 143.82 m^3 ha^{-1} (Table 5). The volumetric estimates derived from radial kernel support vector machines using the P2 approach closely aligned with those obtained from the CURTIS (1967) model. The volume variability tended to be slightly lower with this SVM compared to linear and nonlinear regressions.

Table 5. Volumetric estimates and coefficients of variation (CV) for a seminal stand of *E. cloeziana* at 60 months of age, employing different modeling methods and approaches for applying hypsometric relationships.

Hypsometric ratio	Volume (m^3 ha^{-1})	VC (%)	Volume (m^3 ha^{-1})	VC (%)
	----------- P1 -----------		----------- P2 -----------	
CURTIS (1967)	143,77	8,73	143,79	9,00
Logistics	143,86	8,70	143,86	8,97
VMS (Kernel Radial)	142,69	8,65	143,77	8,73

P1 = estimate of the height of all inventoried stems (estimated heights); P2 = height estimate only for individuals with measured DBH (P2, combination of measured and estimated heights); and SVM = support vector machines.

DISCUSSION

Hypsometric relationships are essential for optimizing the operational routine in forest inventory and understanding the dynamics of forest growth. Eleven functional relationships were established for the estimation of stem height for the seminal stand of E. *cloeziana* at 60 months of age (Tables 2 and 3). Because of the genetic variability that exists in stands planted with seedlings (GUIMARÃES et al. 2019, ABREU NETO et al. 2021), the quality of the adjustments made was considered satisfactory (Table 2 and 3).

The selection of the hypsometric modeling method should consider both statistical considerations (Tables 2 and 3) and biological factors to ensure unbiased and site-representative biometric estimates (GUJARATI & PORTER 2011, CAMPOS & LEITE 2017). The inflation factor of the variance in the adjusted TROREY (1932) model exceeded 10, violating the ordinary least squares method's assumption of absence of multicollinearity (GUJARATI & PORTER 2011). In such circumstances, the regression parameter no longer accurately reflects the inherent effects of a specific independent variable on the dependent variable, instead only partially capturing its true impact.

From a statistical perspective, the hypsometric relationships associated with the CURTIS (1967) model adjustments (linear regression), Logistic (non-linear regression), and SVM with radial basis function kernel demonstrated superior predictive qualities within their respective modeling approaches (Tables 2 and 3; Figure 1). The height-diameter curves of these three hypsometric ratios showed an upward behavior, with monotonic growth and an asymptotic trend (Figure 2), which is biologically expected for plant growth (TAIZ et al. 2017).

However, two limitations were observed in SVMs with radial basis function kernels: the tendency to overestimate the height of stems with smaller DBH and the clear definition of the inflection point (approximately 10cm DBH and 16m height) in their height-diameter curve. The overestimation of stem heights using this SVM directly affected the average stem volume (Table 4). It should be noted that although the sigmoid curve is considered the most biologically appropriate theoretical model for hypsometric relationships, the inflection point often occurs in smaller stems and at ages when the height has not yet been taken (BATISTA et al. 2014).

Both regression methods yielded similar mean estimates for height and volume, differing only in centesimal terms for the first biometric attribute and in ten-thousandths for the second. Although linear regression offers ease of adjustment, it has several inherent limitations associated with the ordinary least squares method (GUJARATI & PORTER 2011, CAMPOS & LEITE 2017). This phenomenon may, in certain instances, render iterative modeling procedures more statistically appealing. For the studied database, the equation derived from fitting the Logistic model demonstrated slightly superior predictive performance in terms of statistical and biological aspects compared to the other established height-diameter relationships.

Hypsometric relationships can be applied with different approaches. The application of hypsometric relationships for estimating the height of all inventoried stems should be approached with considerable caution, as the impact of modeling quality becomes more pronounced in height and volume estimations. Nevertheless, the height dispersion of the inventoried stems was visually greater when combining estimated and observed hypsometric values (P2), particularly above the third quartile (Figure 3). The greater presence of outliers (values beyond the interquartile range) in the stem height distribution compared to those related to individual volumetric estimates suggests that the approaches for applying hypsometric relationships adequately addressed the presence of atypical values and approximated the central tendency of wood production. This robustness is essential for the representativeness and assertiveness of biometric quantification in forest stands (GUJARATI & PORTER 2011, CAMPOS & LEITE 2017). On average and in terms of variance, no statistically significant differences were observed in height and individual volume between the approaches for applying the height-diameter relationship.

The trend of increased variability in individual and per-unit-area volume when combining observed and estimated heights, compared to using only hypsometric estimates (Tables 4 and 5), can be partially attributed to the simplified representation of tree growth in forest ecosystems through mathematical models (Table 1). This finding aligns with BATISTA et al. (2014), which explores the potential for volumetric estimate quality to serve as a variable alternative when considering observed and estimated height values.

Lower variability in volume per unit area is crucial for meeting predetermined sampling error requirements set by state regulations or specific contracts. It is emphasized that sampling error is routinely calculated in conventional forest inventories, such as forest harvest declarations. Therefore, the application of the hypsometric relationship was identified as the most appropriate method for estimating the height of all inventoried tree stems. BATISTA et al. (2014) also propose this approach to mitigate bias in volume prediction, particularly in more heterogeneous commercial stands.

The findings provide valuable insights for advancing forest measurement research and the practical application of height-diameter relationships. The appropriate selection of modeling techniques is crucial for accurately predicting height and volume, while careful planning of the application approach is essential to minimize predictive biases. The application of the height-diameter relationship to estimate the height of all inventoried stems showed promise in reducing biometric variability and streamlining the forest analyst's workflow.

CONCLUSION

Estimating the height of all inventoried tree stems is a viable alternative to using properly established height-diameter relationships and does not compromise forest volume quantification.

Biometric variability tends to be reduced when estimating the height of all inventoried stems rather than combining observed and estimated heights. The coefficients of variation for this latter hypsometric application approach were approximately 4.95% and 2.39% higher compared to the former, for height and volume per unit area of cultivated E. *cloeziana*, respectively.

The calculated volumes derived from estimated heights of all inventoried stems or from a combination of observed and estimated heights do not differ significantly in the study site.

Hypsometric modeling through linear and non-linear regressions, as well as the use of support vector machines, are suitable methodologies for estimating tree height in forest inventories.

ACKNOWLEDGMENTS

To the Federal Institute of Education, Science and Technology of Minas Gerais (IFMG) - Campus of São João Evangelista-MG for all the logistical, structural and financial support for this work.

REFERENCES

ABREU NETO R et al. 2021. Describing the structure and relationship of height and diameter in an old unmanaged *Eucalyptus* spp. plantation. Floresta e Ambiente 28: e20200087.

BATISTA JLF et al. 2014. Quantificação de recursos florestais: árvores, arvoredos e florestas. São Paulo: Oficina de Textos. 384p.

BUENO GF & COSTA EA. 2020. Comparação preditiva de modelos hipsométricos em plantio de eucalipto: equação de regressão e redes neurais artificiais. Enciclopédia Biosfera 17: 654-664.

CAMPOS JCC & LEITE HG. 2017. Mensuração Florestal: perguntas e respostas. 5.ed. Viçosa: Ed. UFV. 636p.

CURTIS RO. 1967. Heigth, diameter and height diameter age equations for second growth Douglas-fir. Forest Science 13: 365-375.

DANTAS D et al. 2020. Reduction of sampling intensity in forest inventories to estimate the total height of eucalyptus trees. Bosque 41: 353-364.

GOMPERTZ B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Philosophical Transactions of the Royal Society of London B: Biological Sciences 115: 513-585.

GUIMARÃES CC et al. 2019. Biomass production and nutritional efficiency in *Eucalyptus* genotypes in the Pampa biome. Journal of Experimental Agriculture International, 34: 1-10.

GUJARATI DN & PORTER DC. 2011. Econometria básica 5.ed. Porto Alegre: AMGH Editora Ltda. 924p.

HENRICKSEN HA. 1950. Height-diameter curve with logarithmic diameter: brief report on a more reliable method of height determination from height curves, introduced by the State Forest Research Branch. Dansk Skovforen Tidsskr 35: 193-202.

IBÁ. 2023. Indústria Brasileira de Árvores. Relatório Anual 2023 – ano base 2022. Disponível em: https://iba.org/datafiles/publicacoes/relatorios/relatorio-anual-iba2023-r.pdf. Acesso em: 25 abr. 2024.

INMET. 2024. Instituto Nacional de Meteorologia. Banco de dados meteorológicos. Disponível em: https://portal.inmet.gov.br/. Acesso em: 25 abr. 2024.

KÖPPEN W. 1936. Das geographische system der klimate. Berlin: Gerbrüder Bornträger. 44p.

KUMAR VA et al. 2019. Prediction of student final exam performance in an introductory programming course: development and validation of the use of a support vector machine-regression model. Asian Journal of Education and e-Learning 7: 2321-2454.

LAFETÁ BO et al. 2021. Comprimentos de seção e altura de fustes na cubagem rigorosa em diferentes espaçamentos de eucalipto. Agrarian, 14: 360-370.

MARTINS JFC et al. 2021. Modelagem hipsométrica de povoamentos de acácia-negra usando linguagem de programação Julia. BIOFIX Scientific Journal 6: 133-152.

MEYER D et al. 2023. e1071: Misc Functions of the Department of Statistics, Probability Theory Group (Formerly: E1071), TU Wien. Disponível em: https://cran.r-project.org/web/packages/e1071/e1071.pdf. Acesso em: 20 dez. 2023.

MIGUEL EP et al. 2018. Modelagem hipsométrica em povoamentos hibrido clonal de *Eucalyptus* hypsometric modeling hybrid clonal *Eucalyptus* stands. Revista Agrarian 11: 159-167.

NICOLETTI MF et al. 2020. Equações hipsométricas, volumétricas e funções de afilamento para *Pinus* spp. Revista de Ciências Agroveterinárias 19: 474-482.

R CORE TEAM 2022. R: A language and environment for statistical computing. Vienna, Austria. Disponível em: https://www.R-project.org/

SANQUETTA MNI et al. 2015. Ajuste de equações hipsométricas para a estimação da altura total de indivíduos jovens de teca. Científica 43: 400-406.

SCOLFORO HF et al. 2015. Hypsometric approaches to Eucalyptus experiments in Brazil. African Journal of Agricultural Research 10: 4176-4184.

SHARMA RP et al. 2019. Modelling individual tree height– diameter relationships for multi-layered and multi-species forests in central Europe. Trees Structure and Function 33: 103-119.

SOARES GM et al. 2021. Artificial neural networks (ANN) for height estimation in a mixed-species plantation of *Eucalyptus globulus* Labill and *Acacia mearnsii* de Wild. Revista Árvore 45: e4512.

SPURR SA. 1962. Measure of point density. Forest Science 8: 85-96.

STOFFELS A & SOEST JV. 1953. The main problems in sample plots. Ned Bosbouwtijdschr 25: 190-199.

TAIZ L et al. 2017. Fisiologia e desenvolvimento vegetal. 6.ed. Porto Alegre: Artmed. 888p.

TÉO SJ & SILVA TC. 2020. General height-diameter equation depending on the stand variables, for *Eucalyptus benthamii*. Floresta e Ambiente 27: e20180302.

TROREY LGA. 1932. A mathematical method for construction of diameter-height curves based on site. Forest Chronicle 8: 121-132.

VAPNIK VN. 1995. The nature of statistical learning theory. 1.ed. New York: Springer-Verlag. 188p.

VIEIRA GC et al. 2018. Prognoses of diameter and height of trees of eucalyptus using artificial intelligence. Science of the Total Environment, 619-620: 1473-1481.