Ensaios e Ciência
ISSN 1415-6938 e ISSN 2178-695X

DOI: https://doi.org/10.17921/1415-6938.2025v29n1p231-246

Central Tendency Measures in Defining Individual Average Volume and Form Factor in Eucalyptus Stands

Medidas de Tendência Central na Definição do Volume Médio e Fator de Forma em Povoamentos de Eucalipto

Received on: 07/05/2024
Accepted on: 18/11/2024

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Abstract
Defining a measure of central tendency that adequately represents average aspects of production under different conditions of asymmetry is a major challenge in the forestry analyst's routine. Scientific investigations that seek operational improvements in inventories contribute to the accuracy of timber resource quantification. This work aimed to evaluate different position measurements in defining the average individual volume and average form factor in eucalypt stands. Continuous inventory was conducted in four forest management units, with 34 permanent plots. Eight criteria

were evaluated to define stems representative of the average individual volume and average form factor, based on dendrometric measurements of central tendency. Quadratic mean diameter provided homogeneous distributions and the lowest percentage errors for volumetric and form estimation of stems. It is concluded that stems with quadratic mean diameter are useful for representing the average individual volume and the average form factor in forest management units. Furthermore, volumetric estimates per unit area can be accurately obtained by employing approaches based on individual average volume and form factor. Measures of central tendency based on height tend to provide less accurate volumetric estimates compared to those based on stem diameter. Central tendency measurements based on height tend to provide less accurate volumetric estimates compared to those based on stem diameter.

Keywords: Height. Diameter. Form Factor. Position Measurements.

Resumo

A definição de uma medida de tendência central que represente adequadamente aspectos médios da produção em distintas condições de assimetria é um grande desafio na rotina do analista florestal. Investigações científicas que buscam melhorias operacionais em inventários contribuem para a assertividade da quantificação de recursos madeireiros. O objetivo do presente trabalho foi avaliar diferentes medidas de posição na definição do volume médio individual e fator de forma médio em povoamentos de eucalipto. O inventário contínuo foi conduzido em quatro unidades de manejo florestal, sendo lançadas 34 parcelas permanentes. Avaliaram-se oito critérios para a definição de fustes representativos do volume médio individual e do fator de forma médio, com base em medidas dendrométricas de tendência central. O diâmetro médio quadrático proporcionou distribuições homogêneas e com os menores erros percentuais para a estimativa volumétrica e de forma dos fustes. Os fustes com diâmetro médio quadrático são úteis para representar o volume médio individual e o fator de forma médio em unidades de manejo florestal. Além disso, estimativas volumétricas por unidade de área podem ser obtidas com precisão ao se empregar abordagens baseadas no volume médio individual e, em especial, no fator de forma. Medidas de tendência central baseadas em altura tendem a fornecer estimativas volumétricas menos acuradas em comparação aquelas com base no diâmetro de fustes.

Palavras-chave: Altura. Diâmetro. Fator de Forma. Medidas de Posição.

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1 Introduction

The quantification of woody stock is a fundamental step in the routine of a mensurationist, whose execution quality influences the accuracy of decision-making and the management of silvicultural production (Ramos-Veintimilla *et al*., 2023). The appropriate selection of stems for rigorous scaling is essential for the reliability of the volumetric estimate available in forest stands.

The reliability of approaches used for the volumetric estimation of commercial plots depends on the representativeness of the selected stems for scaling, the quality of collected data, and the technique adopted for processing the information (Ducey; Kershaw Jr., 2023; Lafetá *et al*., 2021; Miguel *et al*., 2018). The choice of approaches based on form factors or individual mean volume is related to ease of application, cost reduction, and sampling effort, compared to those that employ volumetric and taper modeling (Campos; Leite, 2017).

However, uncertainties associated with the use of form factors and individual mean volume are partially attributed to the diversity of stem shapes, which may vary due to differences in age, site quality, genetic materials, diameter classes, planting spacing, and other silvicultural treatments (Kruchelski *et al*., 2023; Lafetá *et al*., 2021; Lima *et al*., 2023; Peng *et a*l., 2022; Silva *et al*., 2022). Further scientific investigations demonstrating the potential application of both approaches are necessary and contribute to improving the logistics of scaling practices and enhancing the efficiency of inventory processing.

The planning of scaled stem selection must be conducted with great caution to maximize operational efficiency in the field without compromising volume accuracy (Lafetá *et al*., 2021). Although increasing the number of scaled stems makes the sampling procedure increasingly costly, a reduced number of stems may not adequately reflect the dendrometric diversity present in a stand (Campos; Leite, 2017).

Defining a standard central tendency measure that appropriately represents the average productive aspects of stands under different conditions of asymmetry is a major challenge in the routine of a forest analyst. Various measures exist to express the central position of a dataset, with the most well-known in statistical literature being the mean, mode, and median. The arithmetic mean is recommended in situations where the data exhibit a symmetrical distribution, while the median and mode are indicated for scenarios of asymmetry and multimodal distributions, respectively (Hatem et al., 2022; Rubia, 2023).

Central tendency measures of diameter are preferably adopted in the search for specific stems for rigorous scaling due to their strong association with volume and the lower labor intensity required for diameter measurements compared to height measurements (Campos; Leite, 2017). The quadratic mean diameter is the most widely used dendrometric measure in Brazil for selecting model or reference stems for volumetric quantification, as well as for nutritional, physiological, and/or technological analyses of wood (Araújo *et al*., 2024; Barbosa *et al*., 2023; Campos; Leite, 2017; Ducey; Kershaw Jr., 2023; Lafetá *et al*., 2018). This measure corresponds to the diameter of a stem with a sectional area equivalent to the average sectional area within a unit of land area.

A careful selection of stems for rigorous scaling provides essential support for the potential application of form factors or individual mean volume in forest inventories. Based on the above, the following hypotheses were tested: I – strategies based on diameter and height position measures are useful for identifying representative stems of individual mean volume and form factor in eucalyptus stands; II – approaches based on form factors and individual mean volume provide similar volumetric estimates. The objective of this study was to evaluate different dendrometric central tendency measures in defining individual mean volume and mean form factor in eucalyptus stands.

2 Material and Methods

The study was conducted in a clonal plantation of *Eucalyptus urophylla* S. T. Blake, established in a 3.0 × 2.5 m spatial arrangement, located in the central region of the state of Minas Gerais, Brazil. The predominant climate in the region is classified as Cwa according to the Köppen international classification system (Alvarez *et al*., 2013).

Forest Management Unit 1 (FMU1) covered an area of 87.91 ha, with coordinates of longitude 459437m and latitude 7903580m, an average annual precipitation of 1,259 mm, and an average annual temperature of 22.7 ºC. FMU1, FMU2, and FMU3 occupied 42.74 ha (annual averages of 1,043 mm and 23.4 ºC), 77.21 ha (annual averages of 1,043 mm and 23.4 ºC), and 85.57 ha (annual averages of 1,189 mm and 23.0 ºC), with coordinates of longitude 554991, 567041, and 486435, and latitude 7900318, 7957427, and 7921081, respectively.

The inventory was conducted at 36, 48, 60, and 72 months of age, following the operational routine of the forestry company. A total of 11 permanent plots were randomly established in FMU1, 6 plots in FMU2, 10 plots in FMU3, and 7 plots in FMU4. Each plot had a useful area of 400 m² (20 × 20 m). Data were provided on the diameter at breast height (DBH – measured at 1.30 m above ground level, cm) with bark and total height (H, m) estimates for all the inventoried stems. The stems volume (m^3 ind^{-1}) was estimated using specific equations for each FMU, as described in Penido *et al*. (2020).

The form factor at breast height (f) was calculated as the ratio between the estimated real volume and the volume of a hypothetical cylinder (Campos; Leite, 2017). These data were subjected to skewness and kurtosis analysis using the method of moments.

Eight criteria were evaluated for defining representative stems of individual mean volume (IMV, m^3 ind^{-1}) and mean form factor ($\bar{f}$), based on central tendency dendrometric measures. The following dendrometric measures were calculated per FMU:

MD1 – Arithmetic mean of DBH ($\overline{DBH}$, cm);

MD2 – Geometric mean of DBH (*DBH_G*, cm);

MD3 – Harmonic mean of DBH (*DBH_H*, cm);

MD4 – Median of DBH (*DBH_Me*, cm);

MD5 – Quadratic mean diameter (*q*, cm);

MD6 – Arithmetic mean of height ($\bar{H}$, m);

MD7 – Quadratic mean height (*H_q*, m); and

MD8 – Lorey's height (*H_L*).

For each central tendency dendrometric measure, FMU, and age, the individual volume values (V_i, m^3 ind^{-1}) and form factor (f_i) corresponding to the stems whose dimensions most closely matched the analyzed positional measure were identified. The overbark volume (m^3 ha^{-1}) was calculated using two technical approaches: one involving the multiplicative relationship between the identified volume and the number of stems, and the other applying the form factor, as described by Campos and Leite (2017).

The density distribution analysis of the observed individual mean volume and form factor in the continuous forest inventory was conducted, with identification of the percentile occurrence of DBH corresponding to their mean values. The percentage errors of volume and form factor, expressed per stem and per unit area, were used for graphical inspection analysis.

All statistical analyses were performed using R software (R CORE TEAM, 2023).

3 Results and Discussion

The forest inventory included the sampling of 1,597, 1,592, 1,588, 1,586, and 1,584 stems at the ages of 24, 36, 48, 60, and 72 months, respectively. The values for each central tendency dendrometric measure are detailed by management unit in Table 1. In general terms, the positional measures of DBH decreased in the following order: median > quadratic mean diameter > arithmetic mean > geometric mean > harmonic mean, indicating negative or left-skewed asymmetry. The DBH asymmetries were -0.68 (kurtosis = 3.70), -0.73 (kurtosis = 4.50), -0.86 (kurtosis = 5.20), -0.77 (kurtosis = 4.74), and -0.66 (kurtosis = 4.63) throughout the inventoried period.

Table 1 - Descriptive statistics of the dendrometric attributes of inventoried stems in eucalyptus plantations of different ages

Year	IMV	$\overline{DAP}$	DAP_G	DAP_H	DAP_{Me}	q	$\overline{H}$	H_q	H_L
(month)	(m^3 ind^{-1})	------------------ (cm) ------------------					------- m -------		
	---------------------- UMF1 ----------------------								
24	0.0658	10.73	10.64	10.46	10.89	10.80	15.01	15.10	15.18
36	0.1561	13.82	13.69	13.48	14.13	13.93	22.42	22.53	22.66
48	0.2046	15.00	14.84	14.61	15.37	15.13	25.16	25.27	25.53
60	0.2421	15.78	15.60	15.37	16.17	15.92	27.17	27.27	27.55
72	0.2621	16.26	16.09	15.87	16.65	16.41	27.83	27.92	28.18
	---------------------- UMF2 ----------------------								
24	0.0573	9.85	9.74	9.52	9.99	9.92	14.13	14.21	14.31
36	0.1419	13.20	13.09	12.96	13.37	13.29	20.66	20.75	20.81
48	0.2105	14.84	14.71	14.55	15.06	14.96	24.74	24.84	25.04
60	0.2559	15.88	15.73	15.55	16.14	16.01	26.55	26.65	26.89
72	0.2922	16.54	16.39	16.21	16.65	16.67	28.17	28.27	28.52
	---------------------- UMF3 ----------------------								
24	0.0354	8.03	7.87	7.68	7.96	8.18	11.92	12.13	12.45
36	0.0773	10.74	10.60	10.41	10.92	10.85	15.94	16.15	16.25
48	0.1281	12.49	12.34	12.13	12.76	12.61	20.69	20.80	20.93
60	0.1489	13.07	12.90	12.67	13.31	13.20	22.23	22.35	22.54
72	0.1661	13.53	13.36	13.13	13.75	13.66	23.35	23.46	23.70
	---------------------- UMF4 ----------------------								
24	0.0431	9.03	8.92	8.77	9.14	9.12	12.96	12.99	13.08
36	0.1183	12.37	12.24	12.06	12.51	12.47	19.59	19.62	19.73
48	0.1748	13.81	13.64	13.40	14.01	13.95	23.20	23.26	23.46
60	0.2020	14.53	14.34	14.09	14.83	14.69	24.38	24.44	24.66
72	0.2136	14.78	14.59	14.35	15.02	14.93	24.96	25.01	25.27

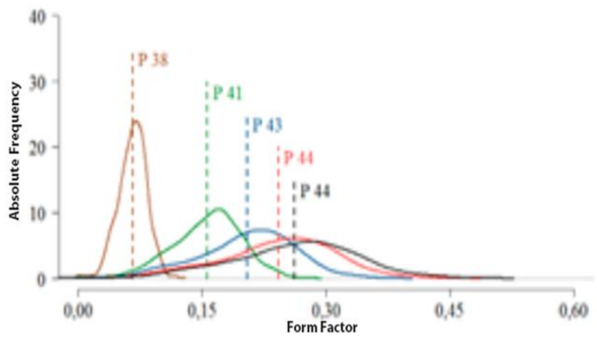
IMV = individual mean volume;
(DAP)̅ = arithmetic mean of DAP;
DAP〗_G = geometric mean of DAP; 〖
DAP〗_H = harmonic mean of DAP; 〖
DAP〗_Me = median of DAP;
q = quadratic mean diameter;
H̅ = arithmetic mean height;
H_q = quadratic mean height;
H_L = Lorey’s height; and
UMF = forest management unit.
Source: research data.

Lorey’s height resulted in the highest hypsometric measurements among the management units, followed by quadratic height and the arithmetic mean height (Table 1). The height asymmetries of all inventoried trees were -0.69 (kurtosis = 4.40) at 24 months, -0.65 (kurtosis = 3.24) at 36 months, -1.11 (kurtosis = 6.52) at 48 months, -0.99 (kurtosis = 5.75) at 60 months, and -0.93 (kurtosis = 5.96) at 72 months of age. The most productive sites at 72 months also exhibited the highest individual mean volumes: UMF2 (315 m³ ha⁻¹) > UMF1 (298 m³ ha⁻¹) > UMF4 (244 m³ ha⁻¹) > UMF3 (209 m³ ha⁻¹).

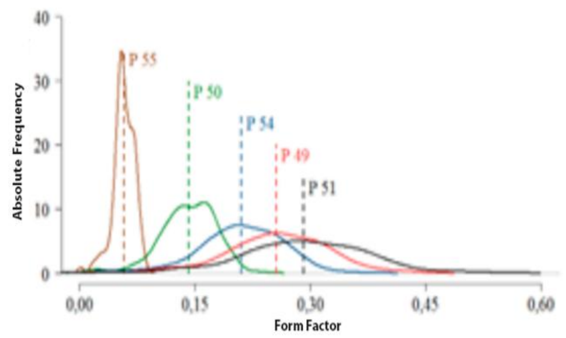
The DAP percentiles corresponding to individual mean volumes did not match those corresponding to mean form factors (Figures 1 and 2). These DAP percentiles ranged from 44% to 55% for individual mean volume and from 21% to 41% for mean form factor at 72 months of age. A trend of rightward shift in the individual volume distribution was observed as the stand aged. In contrast, the form factor distribution tended to shift to the left.

Figure 1 - Density curves of individual volume in eucalyptus stands at different ages. The dashed line represents the individual mean volume; P = DAP percentile at which the individual mean volume occurred; Brown = 24 months; Green = 36 months; Blue = 48 months; Red = 60 months; and Black = 72 months of age

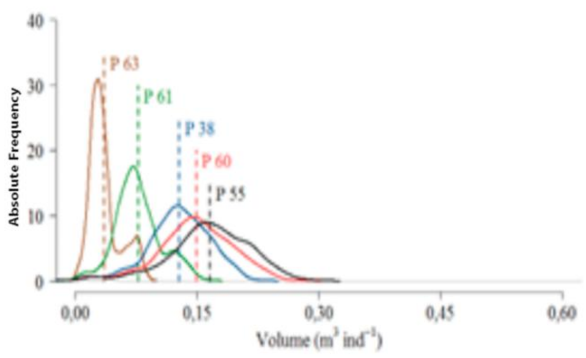
UMF1



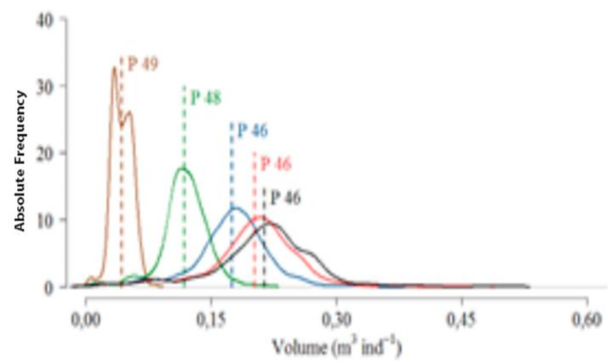
UMF2



UMF3

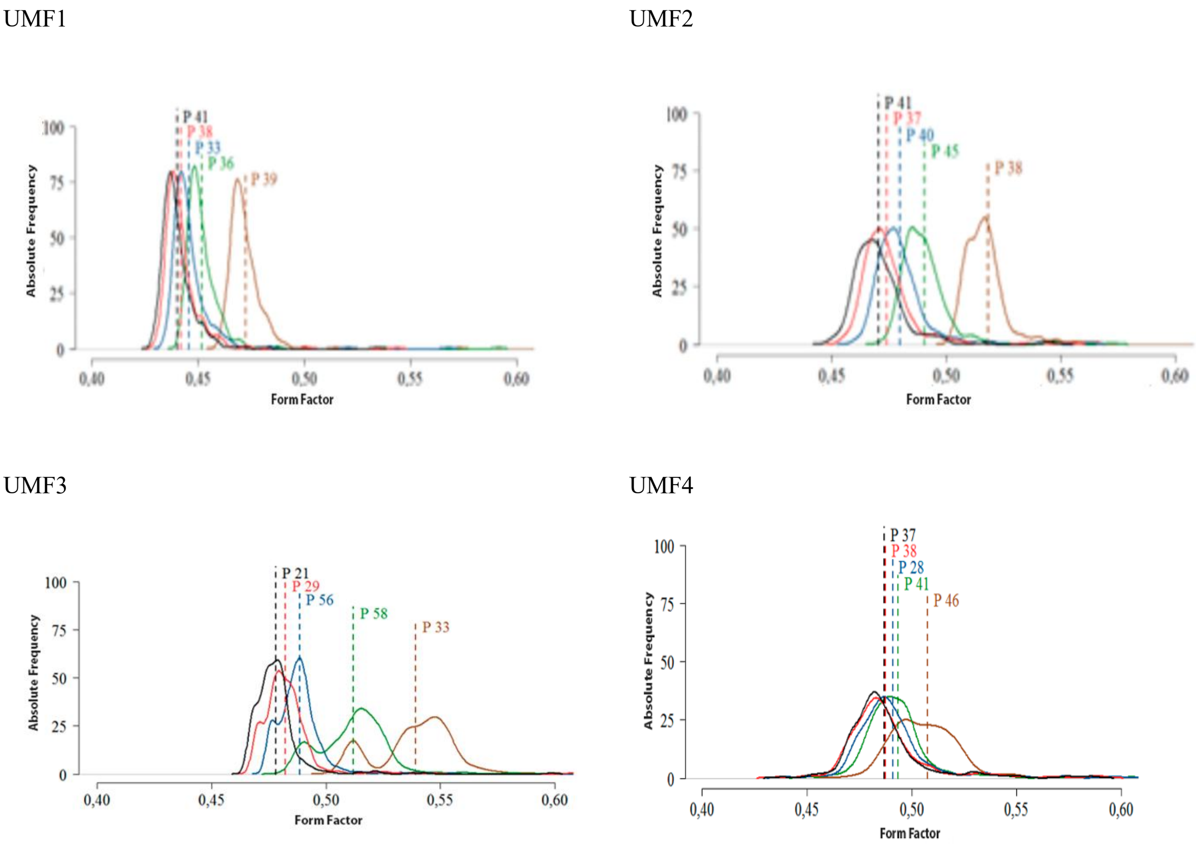


UMF4



Source: research data.

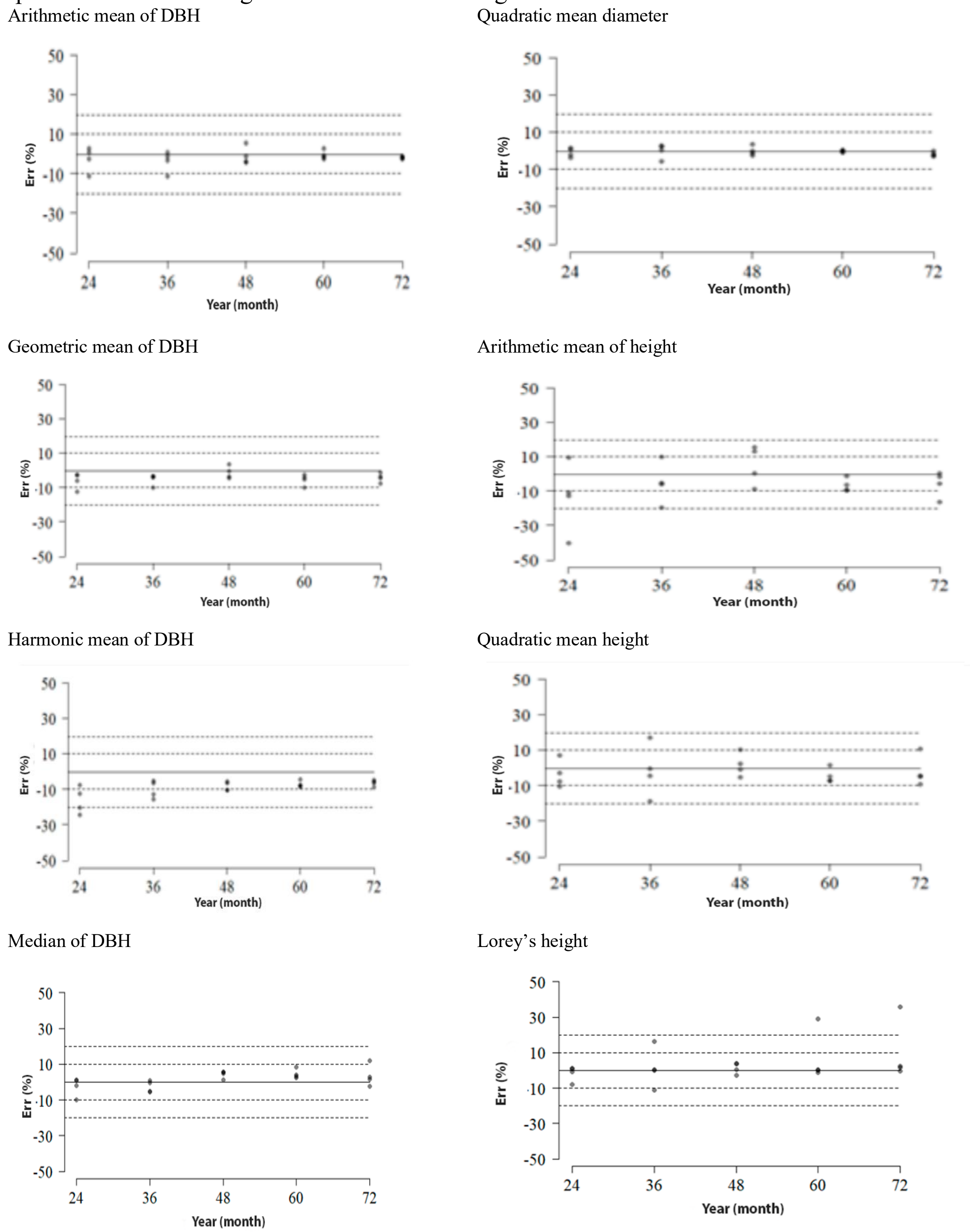
Figure 2 - Density curves of stem form factor in eucalyptus stands of different ages. The dashed line represents the mean form factor; P = DAP percentile at which the mean form factor occurred; Brown = 24 months; Green = 36 months; Blue = 48 months; Red = 60 months; and Black = 72 months of age



Source: research data.

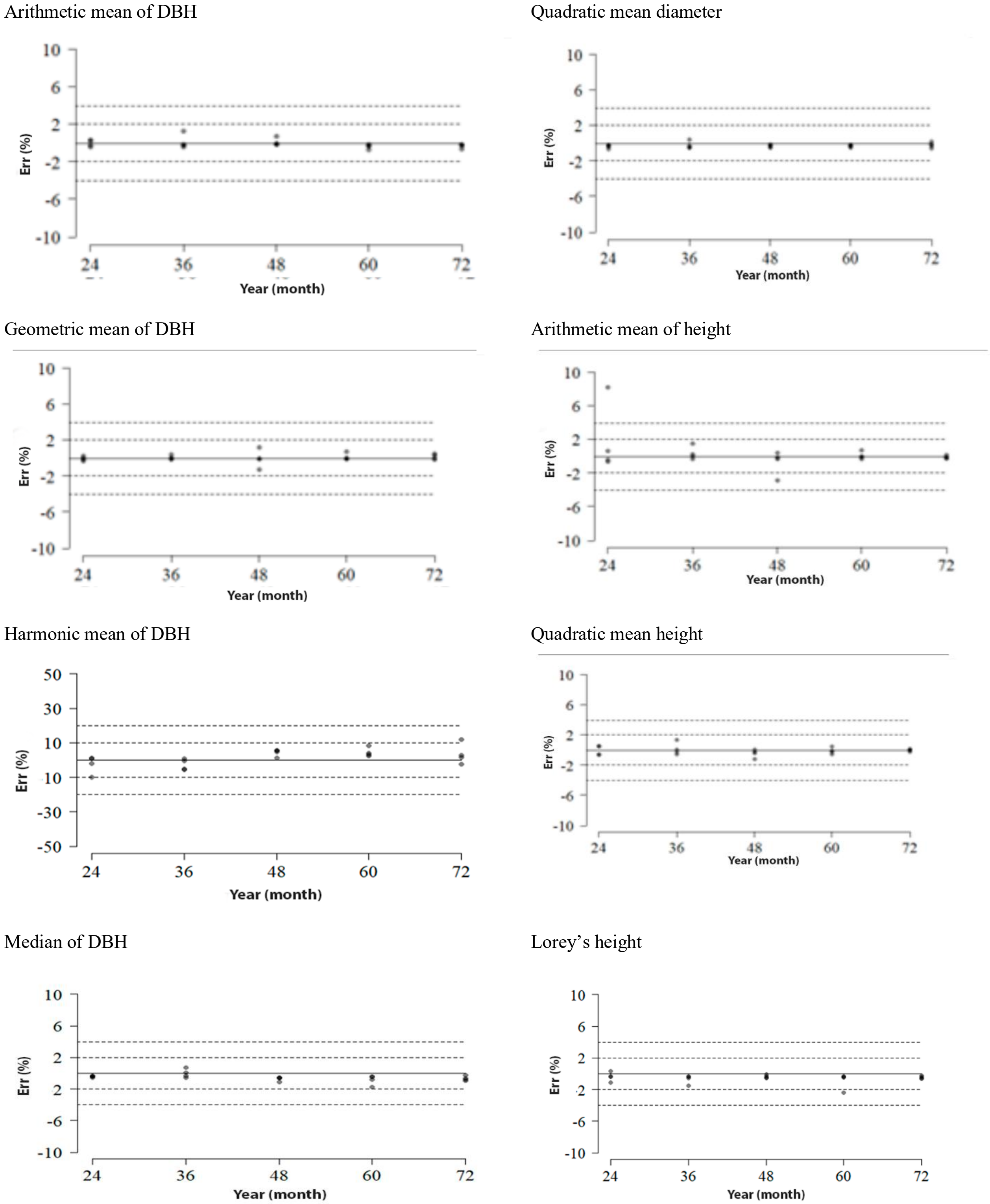
The diameters and total heights of the inventoried stems, whose dimensions most closely matched the central tendency dendrometric measures (Table 1), exhibited absolute differences, in modulus, of at most 0.02 cm and 0.04 m, respectively. It was found that the percentage errors in volume and form factor of the stems identified based on dendrometric measures derived from height showed greater dispersion compared to those calculated based on diameter (Figures 3 and 4). The quadratic mean diameter provided homogeneous distributions with the lowest percentage errors for estimating individual mean volume (-5.76 to 3.70%) and mean form factor (-0.63 to 0.42%) per management unit.

Figure 3 - Estimation error of the individual mean volume with bark for stems defined based on different central tendency measures and dendrometric attributes of eucalyptus plantations. Each point represents a forest management unit at different ages



Source: research data.

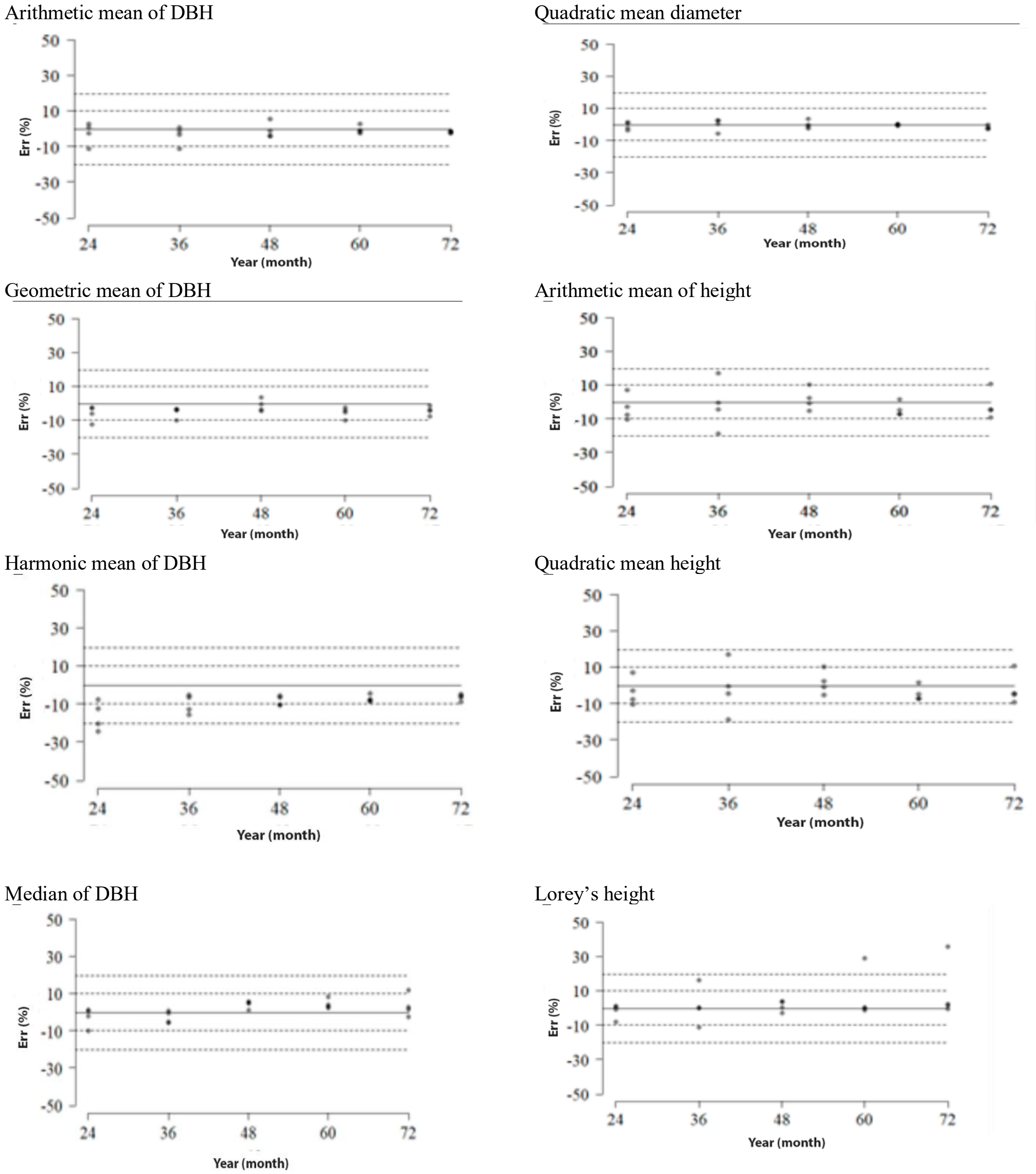
Figure 4 - Estimation of bark form factor error for stems defined based on different central tendency measures and dendrometric attributes of eucalyptus plantations. Each point represents a forest management unit at different ages



Source: research data.

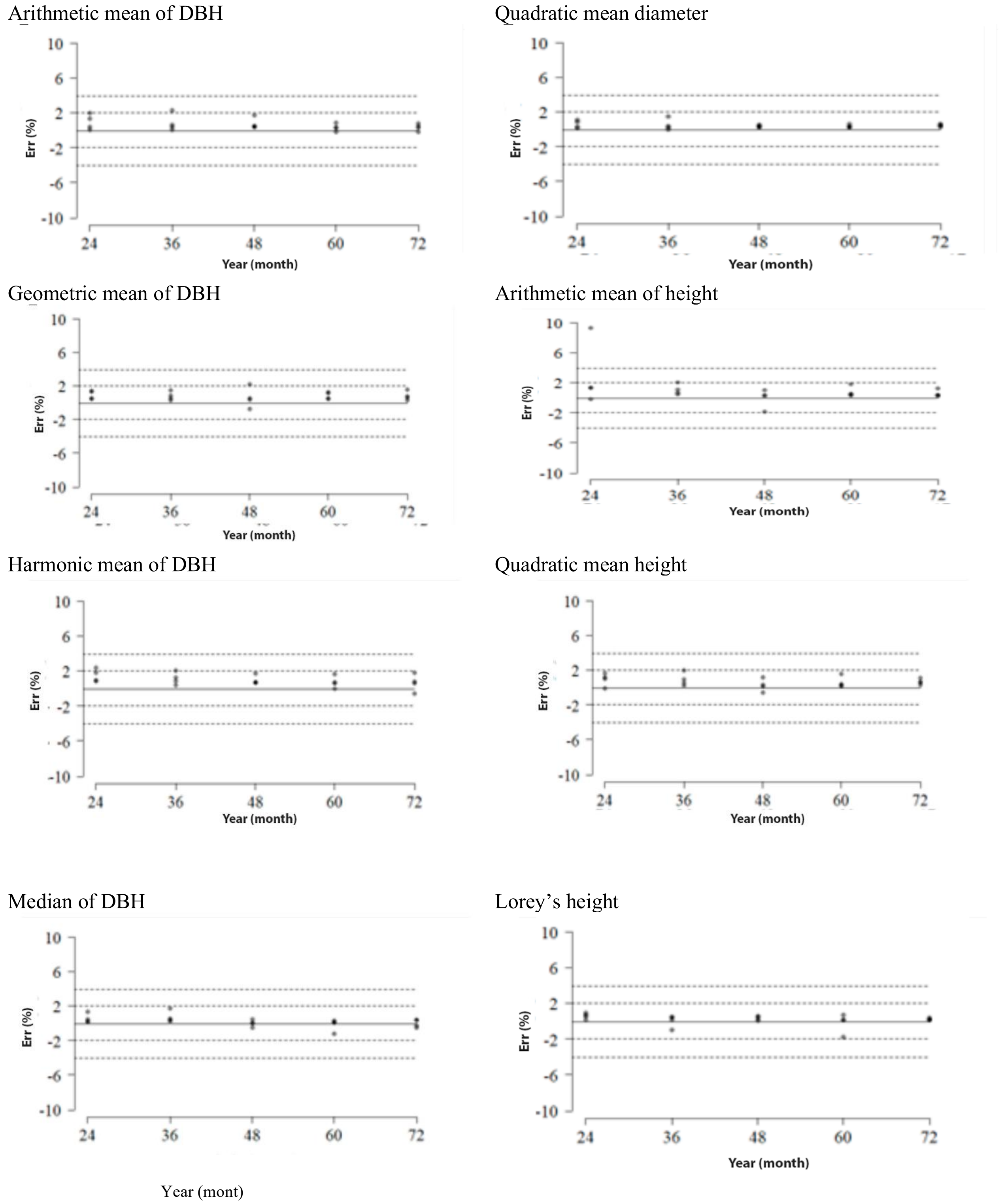
The accuracy in estimating volumes per unit area was not visually similar between the approaches that used the means of individual volume and form factor (Figures 5 and 6). The most biased volumetric estimates per hectare were found when the harmonic mean was adopted as the central tendency dendrometric measure. In these cases, underestimation and overestimation of volume occurred in the approaches using individual mean volume and form factor for calculating volume per unit area, respectively.

Figure 5 - Error distribution of bark-included volume per hectare of eucalyptus stands obtained through the multiplicative relationship between the number of stems and the mean individual volume, defined based on different central tendency measures. Each point represents a forest management unit at different ages.



Source: research data.

Figure 6 - Error distribution of bark-included volume per hectare of eucalyptus stands obtained using the mean form factor, defined based on different central tendency measures. Each point represents a forest management unit at different ages.



Source: research data.

The application of the stem form factor with quadratic mean diameter improved the quality of volumetric estimates per hectare and showed little bias (error ranging from 0.01 to 1.47%), especially for volume quantification at older ages. The multiplicative relationship between the stem volume corresponding to the quadratic mean diameter and the number of inventoried individuals resulted in volumetric estimates per hectare with errors around -5.76 to 3.70% (Figure 5).

The dendrometric characterization of the forest management units through the continuous forest inventory revealed asymmetric distributions of stem diameter and height (Table 1). All asymmetries were negative, indicating a higher abundance of individuals in the larger size classes, resulting in a left-skewed distribution (Rubia, 2023). The leptokurtic behavior observed in these distributions was a consequence of kurtosis values exceeding those of a Gaussian distribution, meaning the distribution was more peaked than a normal distribution (Hatem *et al*., 2022). This phenomenon occurs when there is an excessive concentration of individuals near the arithmetic mean of the dendrometric attribute in question, leading to a more pronounced peak compared to a normal distribution (Santos *et al*., 2019).

The higher individual mean volumes associated with lower form factors ($r = -0.73$; $p \leq 0.01$) were confirmed by the opposite shift in the distribution of individual volume and form factors as the stand aged. The distribution of individual mean volume shifted to the right, while the form factor distribution moved to the left (Figures 1 and 2). The tapering of the stems intensified with increasing age (f̄=0.51\overline{f} = 0.51f=0.51 and 0.47 at 24 and 72 months, respectively), corroborating the findings of Kruchelski *et al*. (2023) and Miguel *et al*. (2018). This described phenomenon was biologically consistent, as cambial meristematic activity intensifies with age relative to apical activity, promoting diameter growth and stem tapering (Liu *et al*., 2023; Taiz *et al*., 2017; Zhou *et al*., 2023).

It was not possible to establish a standard percentile value for DBH corresponding to the means of individual volume (Figure 1) and form factor (Figure 2) for scaling, as dendrometric distributions can assume different skewness and kurtosis depending on site age and productivity potential. Therefore, the use of specific percentile values for diameter distribution, such as 30% (German system mean diameter) or 60% (Weise diameter), proved to be an alternative prone to inaccuracies and biases in identifying representative trees in terms of form and volume.

The central tendency measures calculated using diameter information showed error estimates for the means of individual volume and form factor that were closer to the x-axis compared to those based on height (Figures 3 and 4), providing greater accuracy, which is essential for efficient forest resource management. These findings are particularly relevant in practical contexts, as measuring diameter at breast height is a task that stands out in forest inventories due to its simplicity, speed, and accessibility, in contrast to height measurement (Campos; Leite, 2017; Lafetá *et al*., 2023).

The higher accuracy of stems with quadratic mean diameter in representing the averages of individual volume (errors ranging from -7.43% to 2.76%) and form factor (errors from -0.64% to 0.82%) in the management units may be attributed to its mathematical expression, which assigns more weight to thicker stems. This same effect is expected in volumetric expressions, where larger diameters tend to exert greater influence on volume estimation—briefly explained by the algebraic relationship between cross-sectional area, height, and stem shape (Campos; Leite, 2017). Conversely, the use of geometric and harmonic mean diameters showed a clear underestimation bias for individual volume; however, this bias was not observed in the error estimation of the form factor.

The accuracy of overbark volume quantified per hectare varied between the two technical approaches evaluated (Figures 5 and 6). The lower dispersion of estimation errors in volumetric calculations based on the form factor, compared to those derived from individual mean volume, was associated with the level of detail required for each approach. This is because the second approach primarily relies on general information about stem abundance to calculate volume in a given area, whereas the first is based on a set of individual data, such as height and cross-sectional area.

The stems identified with the quadratic mean diameter provided the most accurate estimates of the overbark volume per hectare, especially when using the technical approach based on the form factor (Figure 6). The volumetric estimates from this approach deviated by less than 1.5% compared to those obtained through volumetric modeling (Penido *et al*., 2020), confirming the potential application of the form factor in forest inventories. It is worth noting that the stem selected for scaling and form factor calculation directly influenced volume accuracy and should therefore be properly identified to reflect the actual productive conditions of the site.

However, it is important to emphasize that the totalization of production based on the stem volume with such a diameter resulted in a residual dispersion ranging from -6% to 6%, which, in some cases of greater uniformity, could still allow for the omission of height measurement and hypsometric modeling in forest inventories. Preliminary analyses on an operational scale are recommended for the potential application of this technical approach.

The results achieved contribute to the development of future research on the measurement and quantification of forest resources. It is essential that the selection of the central tendency measure considers both the nature of the data under study and the underlying objectives of the statistical analysis. This in-depth understanding of statistical techniques fosters the continuous improvement of accuracy and the advancement of operational practices in even-aged stand inventories.

4 Conclusion

Stems with quadratic mean diameter are useful for representing the individual mean volume and the mean form factor in forest management units. Additionally, volumetric estimates per unit area can be accurately obtained using approaches based on individual mean volume and, especially, the form factor.

Central tendency dendrometric measures based on height tend to provide less accurate volumetric estimates compared to those based on stem diameter.

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