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COMPARISON OF METHODS FOR ESTIMATING HEIGHTS FROM COMPLETE STEM ANALYSIS DATA FOR *Pinus taeda*.

COMPARAÇÃO DE MÉTODOS PARA ESTIMATIVA DE ALTURA TOTAL PARA CADA IDADE EM ANÁLISE DE TRONCO COMPLETA DE *Pinus taeda.*

Sebastião do Amaral Machado[1] Luis César Rodrigues da Silva[2] Marco Aurélio Figura[3]
Saulo Jorge Téo[4] Rodrigo Geroni Mendes Nascimento[5]

ABSTRACT

The objective of this research was to compare actual heights at known ages with those estimated by the methods proposed by Graves (1906), Carmean (1972), Lenhart (1972), Newberry (1978), and the Ratio and Graphic methods, in order to identify the most accurate one for *Pinus taeda* from Southern Brazil. That way, six trees aged at least 11 years were used. Cross-sections with 5 cm thickness were collected at heights of 0.10 meters, 0.70 meters, 1.30 meters and so on at every 1 meter along the bole. True height growth for a given age was measured on the section itself by dividing it in two parts along the pith and looking for the exact point where the true annual height growth took place. The accuracy analyses were based on residuals between true heights and those estimated by the tested methods for each age. For this analysis, the relative mean deviation ($D_{\%}$), relative mean absolute deviation ($AbsD_{\%}$), standard deviation of differences (S_d) and sum of squared relative residuals (SSRR) were calculated. These 4 statistics evaluated together, allowed for the identification of the most accurate method for every age. Complementarily, the non paired $t_{0.05}$ test for data was applied to evaluate whether the residuals from each method were significant or not. The results of the analysis indicated that Carmean (1972) and Lenhart (1972) were identical owing to the fact that they estimated the same height value for sections where there was only one growth ring finishing in the same section. This situation occurred for most of the results in this current study. It was concluded that Carmean (1972) and Lenhart (1972) were the best methods for estimating height growth because both produced non-significant residuals for the majority of the trees studied.

Keywords: growth ring; actual heights; cross-section.

RESUMO

O objetivo do presente trabalho foi comparar os valores reais das alturas dos anéis de crescimento anual com os estimados por meio da técnica de análise de tronco pelos métodos de Graves (1906), Carmean (1972), Lenhart (1972), Newberry (1978), Proporções e Gráfico e identificar o mais acurado para árvores de *Pinus taeda* do sul do Brasil. Para isso, foram usadas seis árvores de regeneração natural com idade mínima de 11 anos. Coletaram-se discos de 5 cm de espessura nas alturas 0,1m, 0,7m, 1,30m e a cada 1 m até o fim do tronco. Os valores reais das alturas em cada ano foram medidos diretamente nos troncos, rachando-se as seções entre discos ao longo da medula e procurando pelo ponto exato em que cada idade terminava. As análises de precisão foram baseadas nos resíduos entre os valores reais das alturas em cada ano e os valores estimados para cada método. Para esse fim, foram calculados o desvio médio relativo ($D_{\%}$), desvio médio

1. Engenheiro Florestal, PhD., Professor Sênior do Departamento de Ciências Florestais, Universidade Federal do Paraná, Av. Lothário Meissner, 632 CEP 80210-170, Curitiba (PR). Pesquisador 1A do CNPq. samachado@ufpr.br
2. Engenheiro Florestal, Departamento de Ciências Florestais, Universidade Federal do Paraná, Av. Lothário Meissner, 632 CEP 80210-170, Curitiba (PR). nabravomova@hotmail.com
3. Engenheiro Florestal, Mestrando em Engenharia Florestal, Universidade Federal do Paraná, Av. Lothário Meissner, 632 CEP 80210-170, Curitiba (PR). figura_floresta@hotmail.com
4. Engenheiro Florestal, MSc., Professor da Universidade do Oeste de Santa Catarina, Rua Arcângelo Bompermayer, 8, Bairro Jardim Tarumâ, CEP 89820-000, Xanxerê (SC). sauloteo@yahoo.com.br
5. Graduando em Engenharia Florestal, Universidade Federal do Paraná, Av. Lotháiro Meissner, 632, CEP 80210-170, Curitiba (PR). Bolsista CNPq. geronimendes@hotmail.com

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relativo dos valores em módulo ($AbsD_{\%}$), desvio-padrão (S_d) e soma de quadrado dos desvios relativos (SSRR). Essas quatro estatísticas avaliadas em conjunto, permitiram identificar o método mais preciso para cada ano. Complementarmente foi aplicado o teste de $t_{0,05}$ para dados não pareados, para avaliar se, no geral, os desvios foram significantes ou não. Os resultados das análises indicaram que os métodos de Carmean (1972) e Lenhart (1972) tiveram desempenho idêntico, em função de estimarem a mesma altura quando há apenas um anel de crescimento terminando numa mesma seção. Isso ocorreu na maioria das vezes. Concluiu-se que esses dois métodos foram os melhores por terem gerado desvios não significativos para a maioria das árvores estudadas.

Palavras-chave: anatro; discos; anéis de crescimento; alturas verdadeiras.

INTRODUCTION

The stem analysis is a technique that consists of the examination of the growth ring discs (cross sections) taken from a tree, in order to reconstruct the past growth of that tree. Nevertheless, this can only be used for species that produce clear annual growth rings, most notably conifers. It has been said that Leonardo da Vinci (1452 to 1519) was the first one to state that each ring visible in a transversal cut of a tree trunk corresponds to one year of growth. This led to the development of the stem analysis technique. This analysis technique is very useful to the forest sector when, as stated by Rosot *et al.* (2003), forest companies can use it to verify the average growth of their forests, the reaction of growth to silvicultural treatments or determined management practices, and for developing site index equations.

Spathelf and Nutto (2000) stated that between 1880 and 1950, there had been much activity in Germany in the sense of establishing production tables for the main wood species in Germany. For this, it was necessary to obtain pairs of diameter and height data samples at different ages, and due to the lack of long-term observations for the construction of the first production tables, the German researchers used data from stem analysis.

By analyzing the diameter and the height that each ring reaches within the bole, it is possible to reconstruct the growth of a tree starting from its first year of life. The diameters of the growth rings can be directly measured from the disks taken from the trees, but the height that each growth ring reaches has to be estimated, as measuring it directly from the bole of the tree is extremely difficult. In the literature, there are various methods presented for obtaining these estimates. The concepts are varied and can involve trigonometry or even linear programming. Thus, it is important to carry out a comparative study of these methods in order to identify the best and/or most practical method to be used.

The first work carried out to estimate the height reached for a determined growth ring is attributed to Mlodziansky (1898 apud DYER and BAILEY, 1987, p. 3-4), whose method consists of graphically relating the disc height and tree age for the disc in question; this way, the curve generated by the relationship would give the tree height at any age.

There is another graphic procedure that is the most used by the academic field for teaching the use of the stem analysis technique. This procedure has not been attributed to a specific author and consists of plotting, on a scale, all the disc growth ring diameters and their respective heights. The unions of points for each growth ring for different discs form lines that represent the ring growth. The final part of the line is obtained taking a parallel to the subsequent ring line, as illustrated in Figure 1, or could be resolved by triangle similarity.

Later, Graves (1906), assuming a constant annual height growth, developed a method for estimating the height of the final part of tree growth, using the disc where the growth ring appears for the last time. This way, the section length which contains the end of each ring would be proportionally divided between the number of rings that would terminate in that section. Lenhart (1972), continuing the work of Graves, elaborated a method which divides the section length that contains the end of height growth of one or more rings, equally between these rings.

Carmean (1972), when developed his method, as well as considering a constant annual height growth, took into consideration that, on average in stem analysis, the discs are taken at a time equivalent to one half the growth period. Later, Newberry (1991) proposed a modification to the Carmean (1972) method in order to correct the constant growth ring height underestimates in the sections nearest the total height caused by the method.

In 1978, Newberry, himself, developed a method based on trigonometric relationships, and, according to him, the height growth for each ring can be obtained by multiplying the radius of such ring on the disc where it appears for the last time by the tangent of the angle formed between the disc radius in question and the height of the tree, taken starting from the same disc. The method assumes that this angle, formed between disc radius and the tree's final height, is the same angle formed by the radius of any ring and its final height within the tree, thus it is only necessary to find the tangent of the angle and multiply the value by the radius of the ring for which you wish to know the height to find the value corresponding to this height.

Another method that also uses the growth ring radius of the disc where the ring appears for the last time is the so-called Ratio method. Proposed by Brister and Schultz, it was described by Dyer and Bailey (1987) as a non-published method. This method partitions the section that contains the end of the growth ring into proportions identical to those existing between the growth ring radii on the disc where the ring appears for the last time.

Fabbio *et al*. (1994) proposed the ISSA method based on height/age curves generated by differential equations. The author applied this method for *Pinus nigra*, comparing it to the Carmean (1972) and Lenhart (1972) methods and observed that the ISSA method was more precise when 50 cm sections for stem analysis were used, and the Carmean (1972) method was more precise when two meter sections were used.

Kariuki (2002) also compared his TARG (Tree Annual Radial Growth) method based on the width of the growth rings to estimate the heights reached for each ring with the Carmean (1972), Newberry (1978) and Lenhart (1972) methods and found that the TARG method was more precise for 1.5 to 3.0 meter sections, although the differences generated using the Carmean and Lenhart methods were not significant at a 95% confidence level.

More recently, Lappi (2006) has developed a method for producing height/age curves from stem analysis using linear programming, finding that his method produces better results than the Fabbio *et al.* (1994) method.

Interest in researchers in developing even more accurate methodologies to estimate the height for each growth ring through stem analysis demonstrates the importance of this technique for the forest sector. On the other hand, researchers have also attempted to make it easier to perform, such as Rosot et al (2003) have developed a methodology for carrying out stem analysis using digital disc images obtained in the field. Thus, it is not necessary to take the discs to be studied to the laboratory for later measurement of the growth ring radii. The results demonstrated a difference of 7% for the digital values in relation to the values collected manually.

Dyer and Bailey (1987) were pioneers in

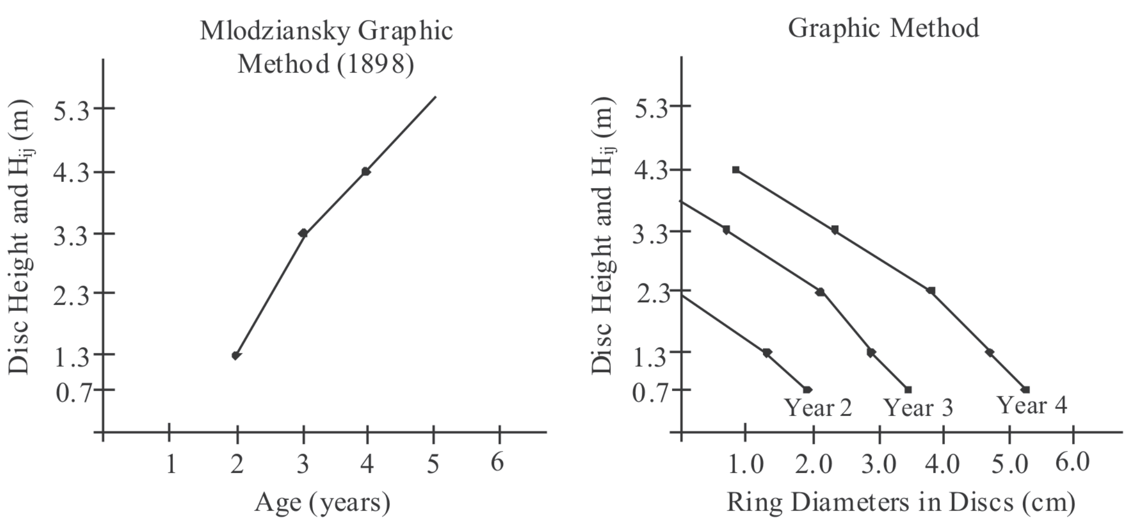


FIGURE 1: Representation of the graphic method proposed by Mlodziansky (1898 apud DYER and BAILEY, 1987, p. 3-4) and the one with widespread use in academic world for the true height estimation (H_{ij}) from the growth ring of a tree.

FIGURA 1: Representação do método gráfico proposto por Mlodziansky (1898 apud DYER and BAILEY, 1987, p. 3-4) e o difundido no meio acadêmico, para se obter a altura (H_{ij}) dos anéis de crescimento de uma árvore.

comparing the methods for estimating growth ring height from stem analysis and, for this reason, they became a reference for other works that appeared afterward. However, this work was not carried out under the external environmental conditions found in Brazil and, because of that, due to the importance of stem analysis techniques to the Brazilian forest sector, the current work, as well as looking for a more accurate method, serves to see if the results found in Brazil are coherent with those from the work carried out in other countries. Thus, the objective became the comparison of the annual growth ring real height values with those obtained using the Graves (1906), Carmean (1972), Lenhart (1972), Newberry (1978), Ratio and Graphic stem analysis techniques and the identification of the most accurate method for *Pinus taeda* trees found in the South of Brazil.

MATERIAL AND METHOD

Study area

The data used for the current study were collected on a plot belonging to the Forest Engineering Course of the Federal University of Paraná (UFPR), located in Curitiba, PR. The local has a small population of naturally regenerated *Pinus taeda* trees, from which the trees for the current work were taken.

The area is located on sloping land and the soil is anthropized. The climate is humid mesothermal subtropical, (Cfb) according to the Köppen classification. The average annual temperatures in the hot and cold months are less than 22 and 18 ºC, respectively, with an average annual temperature of 17º C. The average annual relative humidity of the air and precipitation are 85% and 1,300 to 1,500 mm, respectively. The reference coordinates for the location are 25º 27’ 33” S and 49º 14’ 33” W, at an approximate altitude of 900 meters.

Data collection

A complete stem analysis was carried out for six *Pinus taeda* trees. For this, with each tree already felled, the diameter at breast height (DBH) in centimeters and the total height in meters were measured. Then discs were taken with a thickness of approximately 5 cm at 0.1 meters, 0.7 meters and 1.3 meters and then at every meter along the trunk. The discs were ticketed and grouped for each tree and taken to be dried in a kiln with a controlled temperature of 60°C until the weight remained constant. After this, they were sanded in order to better observe and measure the growth rings. While still in the field, all the sections between the discs were split longitudinally in the direction of the pith with the use of an axe and sledge hammer. The half that provided the best observation of the growth rings was taken to be dried in a conventional kiln. Afterwards for each section, the region next to the pith was sanded to help see the growth rings that bordered or ended in the pith.

In the laboratory, the number of rings was counted for each disc, marking the largest radius ignoring the bark, and then, moving in a clockwise direction and at a 45° angle, two orthogonal diameters were defined with a ball point pen. Thus, each disc had four measurement radii and on these radii, the radii for each one of the growth rings existing in the disc in question were measured, from the most external to the most internal. This way, each growth ring had four radii and the average of the four radii was used to represent the real radius of each one of growth rings. This average is multiplied by 2 resulting in the real diameter for the ring being measured.

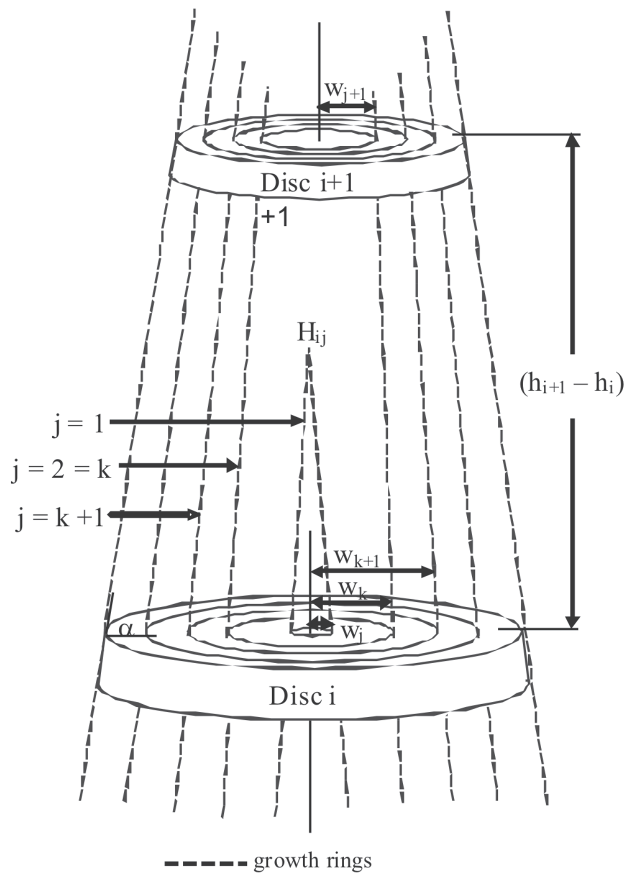
Starting with the disc where each ring studied appears for the last time, the total height for the ring in question using the methods proposed by Graves (1906), Lenhart (1972), Carmean (1972) and Newberry (1978), as well as the Graphic (academic) and Ratio methods was estimated, as described in Table 1. After this, the tree sections where each growth ring ended were taken and the exact location in the section where the ring actually ended was found. This value was the assumed total real height of the growth ring, which was then used as the comparison factor to evaluate the precision of the methods for estimating the total height for each growth ring.

Table 1 provides the mathematical interpretation and illustrates the formula parameters in a hypothetical section between any two discs for the six methods used to estimate the height of each growth ring, using stem analysis, which were later compared with the respective real heights.

Data coverage

Using the real growth ring height observed from the specific section of each tree and the heights estimated by the different methods, a statistical analysis was carried out based on the differences observed between the methods and real (residuals). Firstly, a method was sought that could provide the

TABLE 1: Methods selected for estimating of growth ring height.
TABELA 1: Métodos utilizados para a estimativa da altura de cada ano de crescimento.

Method	Mathematical Expression	An illustration of a section between two discs showing the end of a growth ring
Graves (1906)	$H_{ij} = h_i + j\dfrac{(h_{i+1} - h_i)}{(r_i - r_{i+1})}$	
Lenhart (1972)	$H_{ij} = h_i + j\dfrac{(h_{i+1} - h_i)}{(r_i - r_{i+1} + 1)}$	
Carmean (1972)	$H_{ij} = h_i + \dfrac{(h_{i+1} - h_i)}{[2(r_i - r_{i+1})]} + (j-1)\dfrac{(h_{i+1} - h_i)}{(r_i - r_{i+1})}$	
Newberry (1978)	$H_{ij} = h_i + (tg\alpha)w_j$	
Ratio	$H_{ij} = h_i + \dfrac{(h_{i+1} - h_i)}{\left(\dfrac{w_j}{w_k}\right)}$	
Graphic	$H_{ij} = h_i + w_j\dfrac{(h_{i+1} - h_i)}{(w_k - w_{j+1})}$	

Where: j = each growth ring counting from the pith for each i[th] disc taken from the tree, that is, j = (1,2,...,r_i); r_i = number of growth rings in the i[th] disc; i = disc number from base to top; h_i = height of cut for i[th] disc; H_{ij} = growth ring height corresponding to age j, of the i[th] disc; w_j = radius of j[th] growth ring of disc i; w_k = radius of k[th] growth ring of disc i; w_{j+1} = radius of j[th] growth ring of disc i+1; **á** = angle between disc i and the height of the tree starting at disc i.

least difference in relation to the real value, and afterwards, this was tested to see if this difference was significant or not, using the t-test (p=0.05) for non paired data, the formula of which is

$$t = \frac{\overline{X}_a - \overline{X}_b}{\left(s^2 \dfrac{n_a + n_b}{(n_a)(n_b)}\right)^{0.5}}$$

Where: $\overline{X}$ is the arithmetic mean for groups data a (observed) and b (predicted); s² is the pooled within-group variance; and n is the number of observations in groups a and b.

In order to identify the method with the least error, the current work used the methodology developed by Figueiredo Filho *et al.* (1996) and Figueiredo Filho and Schaff (1999) that could be described as: the Relative mean deviation ($D_{\%}$), Relative mean absolute deviation ($AbsD_{\%}$), standard deviation of differences (S_d) and Sum of squared relative residuals (SSRR) were calculated for the residuals for each growth ring. The equations that represent these statistics are given in Table 2.

As the statistics described in Table 2 are based on errors, the lower these statistics, the lower the error. After the calculation of these statistics, each one of them was put in order from the smallest to the largest for each ring studied and received a number that varied from 1 to 6, that is 1 for first place and 6 for last. Thus, each method had four values for each ring. The sum of the four values was then used to classify the methods for that ring and once again the smallest sum

TABLE 2: Statistics used for evaluation of residuals generated by the method in relation to the true values.
TABELA 2: Estatísticas utilizadas para avaliação dos resíduos gerados pelos métodos em relação aos valores reais.

Statistic	Equation
Relative mean deviation ($D_{\%}$)	$\dfrac{\sum_{i=1}^{n} \dfrac{RES}{VR}}{N}$
Relative mean absolute deviation ($AbsD_{\%}$)	$\dfrac{\sum_{i=1}^{n} \left\lvert \dfrac{RES}{VR} \right\rvert}{N}$
Standard deviation of differences (S_d)	$\sqrt{\dfrac{\sum_{i=1}^{n} \left(RES - \dfrac{RES}{N} \right)^2}{N-1}}$
Sum of squared relative residuals (SSRR)	$\sum_{i=1}^{n} \left(\dfrac{RES}{VR} \right)^2$

Where: RES = (observed height – predict height); VR = observed height; N = number of trees.

indicated the best method for the ring studied. This was carried out for each ring.

In order to verify if the differences between the real height and the heights estimated by the different methods used in the current work were significant, the $t_{0.05}$ test was used in the same way as Dyer and Bailey (1987) used it when they compared the same methods used in the current work for *Pinus taeda* grown in the States of Georgia and North Carolina in the United States. The hypothesis considered is that there was no statistically significant difference between the mean of the heights of the growth ring estimated by the methods and the real heights (H_0), against an alternative hypothesis that there was a significant difference (H_1).

RESULTS AND DISCUSSION

Table 3 presents a summary of the characteristics of the trees used in the complete stem analysis and the number of discs taken at the above-mentioned positions. Based on the work by Dyer and Bailey (1987), Table 4 presents the stem analysis results for tree 2, as an example. This table presents in which disc (and its collection height) each age ring appears for the last time as well as the diameter of the ring in that disc. The heights estimated for these rings calculated by the different methods are also shown, as well as the real heights that they reached within the bole. A table like this one was created for each one of the six trees.

Based on the data from the six tables, an average percentage difference between the height for each year's growth estimated by the different methods

TABLE 3: Characteristics of trees utilized for the complete stem analysis.
TABELA 3: Características das Árvores Utilizadas para Análise de Tronco Completa.

Species	Tree N.	DBH (cm)	Total height (m)	Stump height (m)	Age (year)	Number of discs
Pinus taeda	1	19.0	15.89	0.10	13	17
	2	19.5	13.39	0.10	11	14
	3	16.3	13.95	0.10	14	15
	4	13.8	15.24	0.10	15	16
	5	15.6	15.00	0.15	16	16
	6	16.3	12.70	0.10	15	14

TABLE 4: Data from stem analysis and estimated heights for tree 2 that was 11 years old.
TABELA 4: Dados de análise de tronco e alturas estimadas para a árvore 2, com 11 anos de idade.

Disc number	Disc height (m)	Number of rings	Ring age (Year)	Diameter		Predicted height						Real height
				ring 1	ring 2	Graphic	Newbrry	Ratio	Carmean	Lenhart	Graves	
				(cm)		(m)						
1	0.10	11										
2	0.70	11										
3	1.30	11	1	1.20		02.00	02.01	02.30	01.80	01.80	02.30	01.47
4	2.30	10	2	1.25		03.00	02.99	03.30	02.80	02.80	03.30	02.54
5	3.30	9	3	2.15		04.30	04.30	04.30	03.80	03.80	04.30	03.80
6	4.30	8	4	2.40		05.30	05.30	05.30	04.80	04.80	05.30	04.98
7	5.30	7	5	2.25		06.30	06.30	07.30	06.30	06.30	07.30	06.19
8	6.30	6										
9	7.30	6	6	1.45		08.04	08.03	08.30	07.80	07.80	08.30	07.44
10	8.30	5	7	1.65		09.08	09.09	09.30	08.80	08.80	09.30	08.59
11	9.30	4	8	2.00		10.20	10.21	10.30	09.80	09.80	10.30	09.60
12	10.30	3	9	2.10		11.30	11.30	11.30	10.80	10.80	11.30	10.95
13	11.30	2	10	2.20	2.45	12.30	12.30	12.30	11.80	11.80	12.30	12.15

and the real height measured in the section that contained the rings was prepared for the six trees. The result is shown in Figure 2, where it can be seen that an overall height overestimation trend exists for the height of each year's growth. It is even found that these differences from the real values were larger in the first year's growth and was smaller in the final years' growth. A possible explanation for this is that, during the first years, the trees have lower total real heights than in the latter years and that, supposing that each method's absolute error remains constant throughout the years, the expectation is that the ratio between the absolute error and the lower total heights result in larger relative errors

Another curious fact that can be seen in Figure 2 is the pairing of the methods, that is, the residual curves for methods appear to be grouped two by two. This occurs in function of the similarity of

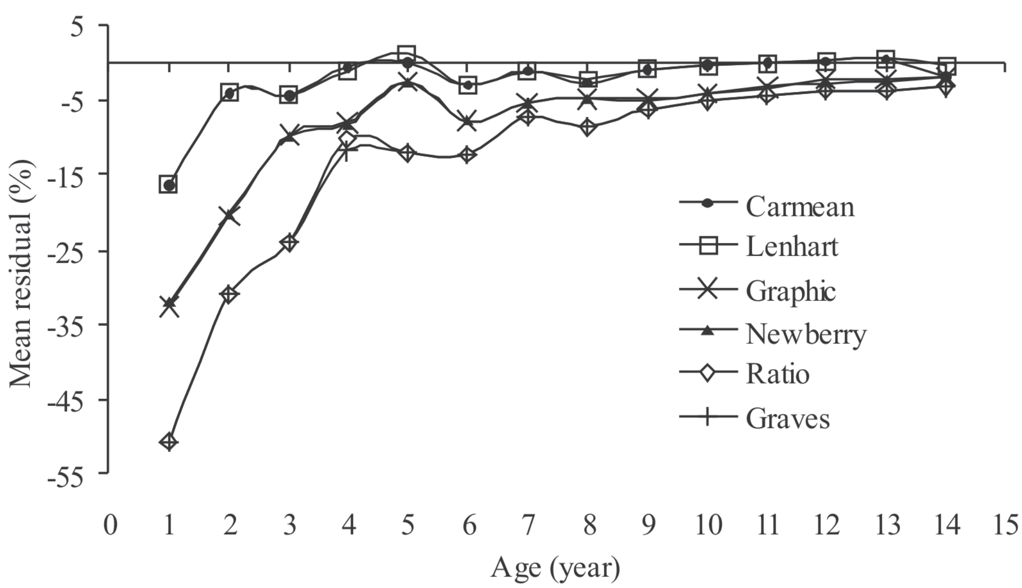


FIGURE 2: Mean residuals in percentage of the different methods of height estimate of the internal growth rings in each tree.
FIGURA 2: Resíduos médios, em porcentagem, dos diferentes métodos de estimativa da altura dos anéis de crescimento em cada árvore.

the concepts between the methods and the way in which the stem analysis was used. One meter sections were predominately used and it occurred that in almost all cases only one ring terminated in any section studied, that is, there was only one height to be estimated in the section studied, and it occurred that two by two they estimated the same height, presenting differences in pairs only when there was more than one growth ring height to be estimated from each separate section. Thus, there was a perceptual difference between the residual curves for the methods only if many sections contained more than one growth ring for the height to be estimated.

The trees selected for this study were taken from a naturally regenerated population and for this reason do not have the same age and for the comparison of the results between the trees it is necessary that there is the same number of growth rings in all trees. The number of these rings to be used in all trees was determined. As the tree with the lowest age was 11 years-old and the last year could not be used for an estimate because this year didn't contain the tree total height that could be measured in the field, only the heights for the previous years were estimated. Thus, only the growth heights were analyzed for year 1 to 10. This limited the analysis to the first ten years because it was the maximum age that permitted the use of all six trees at the same time.

The statistics calculated based on the residuals for each method, for each year's growth, were grouped in Table 5, and based on this, a performance classification was carried out for each method for each ring. As an example of the process, using growth ring 1 the value of each of the SSRR, AbsD%, D% and S_d statistics received a note that varied between 1 and 6, such that, 1 was for the method that produced the lowest value and 6 for the method that produced the largest value. Thus, it can be seen that the Graves method received a note 4 for the SSRR statistic (due to producing the fourth lowest

TABLE 5: Statistics of the methods for estimating total height growth of the rings from the first to tenth year

TABELA 5: Estatística dos resíduos gerados pelos métodos para estimar a altura total dos anéis de crescimento, do Primeiro ao Décimo Ano.

Method	Statistic	Growth ring										Mean
		Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8	Ring 9	Ring 10	
Graves	SSRR	1.70	0.78	0.46	0.09	0.12	0.14	0.03	0.05	0.02	0.02	0.34
	AbsD%	50.84	31.02	24.07	11.93	12.03	12.45	7.30	8.67	6.17	5.14	16.96
	D%	-50.84	-31.02	-24.07	-11.93	-12.03	-12.45	-7.30	-8.67	-6.17	-5.14	-16.96
	Sd	0.47	0.56	0.68	0.45	0.73	0.84	0.52	0.73	0.55	0.52	0.61
Lenhart	SSRR	0.25	0.14	0.08	0.01	0.01	0.03	0.01	0.01	0.002	0.002	0.05
	AbsD%	16.71	11.34	8.73	4.05	3.19	5.90	2.55	2.78	1.39	1.65	5.83
	D%	-16.38	-3.97	-4.23	-1.05	1.29	-2.93	-1.27	-2.13	-0.83	-0.31	-3.18
	Sd	0.18	0.24	0.27	0.16	0.17	0.37	0.19	0.23	0.15	0.19	0.22
Carmean	SSRR	0.25	0.14	0.08	0.01	0.01	0.03	0.004	0.01	0.002	0.002	0.05
	AbsD%	16.71	11.34	8.73	3.61	3.64	5.90	2.36	3.51	1.39	1.65	5.88
	D%	-16.38	-3.97	-4.23	-0.61	-0.14	-2.93	-1.08	-2.86	-0.83	-0.31	-3.33
	Sd	0.18	0.24	0.27	0.15	0.18	0.37	0.17	0.32	0.15	0.19	0.22
Ratio	SSRR	1.70	0.78	0.46	0.08	0.12	0.14	0.03	0.05	0.02	0.02	0.34
	AbsD%	50.84	31.02	24.07	10.17	12.03	12.45	7.30	8.67	6.17	5.14	16.78
	D%	-50.84	-31.02	-24.07	-10.17	-12.03	-12.45	-7.30	-8.67	-6.17	-5.14	-16.78
	Sd	0.47	0.56	0.68	0.42	0.73	0.84	0.52	0.73	0.55	0.52	0.60
Newberry	SSRR	0.69	0.30	0.08	0.05	0.01	0.04	0.02	0.02	0.02	0.01	0.12
	AbsD%	32.18	20.30	9.81	8.36	3.01	7.86	5.36	4.91	5.09	4.00	10.09
	D%	-32.18	-20.30	-9.81	-8.36	-2.72	-7.86	-5.36	-4.91	-5.09	-4.00	-10.06
	Sd	0.31	0.37	0.30	0.33	0.16	0.51	0.38	0.39	0.46	0.40	0.36
Graphic	SSRR	0.70	0.31	0.08	0.05	0.01	0.04	0.02	0.01	0.02	0.01	0.12
	AbsD%	32.49	20.53	9.64	8.20	2.85	7.91	5.44	4.83	4.95	3.98	10.08
	D%	-32.49	-20.53	-9.64	-8.20	-2.55	-7.91	-5.44	-4.83	-4.95	-3.98	-10.05
	Sd	0.31	0.38	0.30	0.33	0.15	0.51	0.39	0.38	0.45	0.40	0.36

TABLE 6: Performance of the methods for estimating of the growth ring height related to true height, based on the statistics SSRR, AbsD%, D% and Sd.

TABELA 6: Desempenho dos Métodos de Estimativa da Altura dos Anéis de Crescimento, em Relação à Altura Real, Baseada nas Estatísticas SSRR, AbsD%, D% e Sd.

Method	Graves	Lenhart	Carmean	Ratio	Newberry	Graphic
Ring 1	15 (4)	4 (1)	4 (1)	15 (4)	8 (2)	11 (3)
Ring 2	16 (4)	4 (1)	4 (1)	16 (4)	8 (2)	12 (3)
Ring 3	15 (4)	6 (1)	6 (1)	15 (4)	11 (3)	7 (2)
Ring 4	22 (6)	8 (2)	4 (1)	20 (5)	16 (4)	12 (3)
Ring 5	19 (4)	10 (2)	12 (3)	19 (4)	10 (2)	6 (1)
Ring 6	14 (4)	4 (1)	4 (1)	14 (4)	8 (2)	10 (3)
Ring 7	18 (5)	8 (2)	4 (1)	18 (5)	12 (3)	14 (4)
Ring 8	19 (5)	4 (1)	8 (2)	19 (5)	15 (4)	12 (3)
Ring 9	16 (4)	4 (1)	4 (1)	16 (4)	12 (3)	8 (2)
Ring 10	13 (4)	4 (1)	4 (1)	13 (4)	9 (3)	8 (2)
Total	44 (5)	13 (1)	13 (1)	43 (4)	28 (3)	26 (2)

results), note 4 for the AbsD% statistic, note 4 for the D% statistic and note 3 for the S_d statistic. For ring 1, the sum of the notes (15) put the Graves method in fourth place amongst the methods, value (4), and so forth for each ring. By totaling all the notes for the Graves method, the sum 44 puts the Graves method in fifth place in the overall evaluation as shown by the value (5) beside the value 44.

It can be further seen in Table 6 that, overall, the Carmean (1972) and Lenhart (1972) methods tied for first place, that is, they are the methods that resulted in the estimated height values closer to real growth for each growth year.

When one uses the t-test as performed by Dyer and Bailey (1987), one gets the results observed in Table 7 where it is seen that all the methods estimated the height for each growth ring with a significant difference at the 99% level of confidence in relation to the real value. These authors studied 30 trees from the same region and obtained a non significant result for the Carmean method and further stated that this method was the best for 78.6% of the trees studied by them. This means that they did not obtain non significant results for all trees, and that, if there are more trees with non significant growth ring height estimate differences, the better the method. Then, it is enough to use the t-test for each tree to find out the performance of each method.

It was then decided to apply the t-test tree by tree, considering all growth rings for each tree. The result, as seen in Table 8, was two of the six trees had significant results for all methods. For the other trees,

TABLE 7: Statistic summary of the growth ring height residuals for considering the 10 first observed years.

TABELA 7: Resumo Estatístico dos Resíduos para a Altura dos Anéis de Crescimento, Considerando os 10 Primeiros Anos Observados.

Method	Numger of obsevations	Minimum value	Maximum value	Absolute mean	mean	Standart deviation	Statistic test ($t_{0.05}$)
		Meters					
Graves	60	-1.665	-0.069	0.584	-0.603	0.3102	-15.06**
Lenhart	60	-0.665	0.431	0.121	-0.086	0.2316	-2.88**
Carmean	60	-0.694	0.431	0.146	-0.095	0.2392	-3.07**
Proporções	60	-1.665	-0.069	1.096	-0.597	0.3161	-14.64**
Newberry	60	-0.880	0.045	0.880	-0.367	0.1797	-15.8**
Graphic	60	-0.880	0.045	0.500	-0.365	0.1812	-15.58**

** = significant at 0.01 level.

TABLE 8: Result of the residual statistical tests for the growth ring height from each tree, considering the 10 first years.

TABELA 8: Resultados dos Testes Estatísticos dos Resíduos para a Altura dos Anéis de Crescimento, de Cada Árvore, Considerando os 10 Primeiros Anos.

Method	Number of Observation	Statistical Test ($t_{0.05}$)					
		Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6
Graves	10	-7.91**	-6.79**	-5.23**	-6.39**	-5.82**	-8.56**
Lenhart	10	-3.99**	-1.058^{ns}	-2.26*	-0.75^{ns}	0.10^{ns}	-0.37^{ns}
Carmean	10	-3.99**	-1.058^{ns}	-2.26*	-0.75^{ns}	0.10^{ns}	-0.81^{ns}
Ratio	10	-7.91**	-6.79**	-5.23**	-6.39**	-5.82**	-6.67**
Newberry	10	-5.36**	-7.47**	-6.02**	-6.93**	-6.11**	-9.36**
Graphic	10	-5.44**	-7.49**	-5.89**	-6.97**	-6.17**	-8.17**

ns = non significant at 0.05 level; *significant at 0.05 level; **significant at 0.01 level.

the growth ring height estimated using the Carmean (1972) and Lenhart (1972) methods showed non-significant differences at a 95% confidence level.

The t-test was once again carried out considering all the trees, less the significant ones, and the result shown in Table 9 shows that, without these trees, the growth ring height estimate differences produced by the Carmean (1972) and Lenhart (1972) methods were not significant. This indicated that overall they were the best methods, firstly because on the performance based on the SSRR, AbsD%, D% and Sd statistics these two methods produced the results nearest to the real and secondly because, according to the t-test, these results were not significant for the majority of the trees. For the other methods, there were significant overestimates for the growth ring height.

The results found in the present work are coherent with those ones found by Dyer and Bailey (1978). At the time, the authors concluded that the Carmean (1972) method was the most accurate for estimating the growth ring height using the stem analysis technique. In the present work, the Carmean (1972) method, together with that of Lenhart (1972), was the best method for 67% of the trees studied.

As mentioned above, the Lenhart (1972) method had an identical performance to that of Carmean (1972) as a consequence of there being only one growth ring ending in one section in almost all cases and by the mathematical formulation of the methods, themselves, as when this occurs the two methods estimate the same height for growth ring in question. Dyer and Bailey (1978) worked with many sections that contained the end of more than one growth ring and they only were concerned with estimating the height of the first ring that ended in each section. Although it had not been observed by them, the fact that the Lenhart (1972) method had not been better than that of Carmean (1972) for estimating the growth ring height, in their work, is an indication

TABLE 9: Statistical summary of the residuals for the growth ring height, excluding trees 1 and 3.

TABELA 9: Resumo Estatístico dos Resíduos para a Altura dos Anéis de Crescimento, Excluindo as Árvores 1 e 3.

Method	Number of Observations	Minimum Value	Maximum Value	Absolute Mean	Mean	Standart Deviation	Statistical Test ($t_{0.05}$)
		meters					
Graves	40	-1.121	-0.069	0.765	-0.534	0.257	-13.14**
Lenhart	40	-0.363	0.431	0.000	-0.036	0.222	-1.02^{ns}
Carmean	40	-0.363	0.431	0.182	-0.042	0.220	-1.22^{ns}
Ratio	40	-1.121	-0.069	1.112	-0.525	0.265	-12.52**
Newberry	40	-0.630	-0.027	0.593	-0.363	0.161	-14.25**
Graphic	40	-0.620	-0.007	0.493	-0.359	0.162	-14.04**

** = significant at 0.01 level; ns = non significant at 0.05 level.

that when more than one growth ring ends in the same section, the Carmean (1972) method is more accurate than that of Lenhart (1972); otherwise, the two results are very much the same, depending on the number of sections that contain the end of only one growth ring.

Overall, it is found that the Carmean (1972) method is the best to estimate the growth ring height using the stem analysis technique with one meter length, or longer, sections. This can be seen in the work that has already been carried out comparing various methods to estimate growth ring height. Of the work that identifies the Carmean (1972) method as the best method, Dyer and Bailey (1978) used sections of 5 feet or 1.52 meters (1 foot = 30.48 cm) and Fabbio (1994) used 2.0 meter sections, and Kariuki (2002) observed that the Carmean (1972) method, while not being the best, produced non-significant differences for 1.5 and 3.0 meter length sections.

Thus for the time being, the Carmean (1972) method is the most interesting to be associated with the stem analysis technique and the best when used for teaching the application of this technique in the academic world.

CONCLUSIONS

The Carmean (1972) and Lenhart (1972) methods were the best for estimating the growth ring height using the stem analysis technique with 1 meter length sections. They overestimated the ring heights; however, this difference was not significant at the 0.05 probability level, for the majority of the trees;

After observing the work of other authors, Carmean (1972), who considered constant annual growth, is superior to Lenhart (1972), when the sections used under the stem analysis technique have more than one ring terminating in the same section;

For all the trees studied, all the other methods tested to estimate growth ring height produced significant differences at the 99% confidence level when compared with the real height values for the same rings heights.

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