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Modeling growth of total height using early data from forest inventories in fast growing *Eucalyptus* spp. plantations

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ABSTRACT: This work evaluated the growth trend represented by three biological models used for modeling forest growth and production (Schumacher; Chapman-Richards; Logistic). These curves were chosen because they are widely used by forest science professionals. The functions were adjusted under the hypothesis that there is influence of the initial, 6 and 12 month measurements on the shape of the production curves and, consequently, in the estimate of their parameters. The data that formed the adjustment basis were generated by the continuous monitoring performed at 6, 12, and 24 months and later at each 12 months in order to yield the growth patterns for the evaluated plantations. The results herein presented allow us to conclude that independently of the type of adjustment, the Chapman-Richards function was the one that exhibited the best statistics, with the BIAS values reduced in up to 30% when compared to the others. The Schumacher function presented the worst performance among the proposed criteria in this study. So, given the results obtained, there was a strong influence of measurements at ages younger than 2 years in the logistic model, and therefore, we suggest a broader reflection about the growth and production issue, especially for the use of biometric models applied to forest production forecast, in which stability and adherence of the curves to the data are expected.

Modelagem do crescimento da altura total por meio da inclusão de medições precoces em plantios de rápido crescimento de *Eucalyptus* spp

RESUMO: Neste trabalho foi avaliada a tendência de crescimento representada por três modelos biológicos empregados na modelagem do crescimento e da produção florestal (Schumacher; Chapman-Richards; Logística). Optou-se por estas curvas por serem amplamente utilizadas por profissionais da ciência florestal. As funções foram ajustadas sob a hipótese de que há influência das medições iniciais, 6 e 12 meses, no formato das curvas de crescimento para a altura média do povoamento, e por consequência na estimativa de seus parâmetros. Os dados, que compuseram a base de ajuste foram originados do monitoramento contínuo realizado aos 6, 12, 24 meses e posteriormente a cada 12 meses de forma a gerar os padrões de crescimento para a variável analisada. Os resultados permitiram inferir que independente da forma de ajuste, a função de Chapman-Richards foi a que apresentou as melhores estatísticas, com valores de BIAS reduzidos em até 30% quando comparada às demais. A função de Schumacher foi a que apresentou o desempenho menos satisfatório dentre os critérios propostos no estudo. E assim, diante dos resultados obtidos, observou-se uma forte influência das medições em idades inferiores a 2 anos no modelo logístico, e, portanto, sugerimos uma reflexão mais ampla acerca do tema crescimento e produção, em especial, para o uso de modelos biométricos aplicados em projeções da produção florestal, em que, se deseja estabilidade e aderência das curvas aos dados.

Introduction

The study of forest growth and production is extremely relevant for the supply of forest-based projects. Wood supplying plans require updated information as well as the forecast of the forest production (Soares et al., 1995). For this purpose, growth and production models are adjusted to data from forest inventories. In Brazil, the most common type of inventory to follow the growth of forest populations is the continuous forest inventory - CFI (Reis et al., 2016). Therefore, it is common to install permanent sample units when the populations reach two or three years, and, later, yearly remeasured (Kanegae Junior et al., 2006; Scolforo and Mello 2006).

Many different studies have been performed aiming to evaluate the accuracy of the estimates of growth and production models in forest plantations such as the works of Calegario et al. (2005); Martins et al. (2014); Scolforo et al. (2016); and Mendonça et al. (2017). However, these studies have always used CFI data with measurements taken from permanently installed plots 24 months after the planting date.

Other types of inventories are made with different purposes at 6 and 12 months (quality inventory) and also in ages close to harvest time (pre-cut inventory – PCI). However, most of the forest growth and production studies discard the use of the information generated initially, like the quality forest inventories at 6 and 12 months of age. Since these obtained data are not used to estimate the growth of populations/individuals, there is lack of information about their effect on the accuracy of the estimates as well as in the shape of the forest growth and production.

Thus, this work aims to analyze the effect of data from early inventories (6 and 12 months) in the shape of the curve and accuracy of the estimates of the growth in height of populations of fast growing *Eucalyptus* spp in Brazil.

Material and Methods

Data

The data used in this study came from measurements of permanent plots of forest inventory in monoclonal plantings of hybrids of *Eucalyptus grandis* and *Eucalyptus urophylla* planting with a spacing of 3 x 3m. The settings and measurements of the plots were performed at six months, with new measurements being made again at 12, 24, 36, 48, 60, and 72 months of age.

The average growth in total height of the trees present in the permanent plot was checked to evaluate the effect of the early measures in growth modeling. The descriptive statistics of the total heights of the trees of the trees sampled in the permanent plots are shown in Table 1.

Table 1 – Descriptive summary for the variable total height in the different age classes

Age (months)	Mean (m)	Standard deviation (m)	Coefficient of Variation (%)
< 12	2.34	0.9563	40.9
12-24	12.52	2.8662	22.9
24-36	15.30	2.1628	14.1
36-48	20.86	1.7032	8.2
48-60	22.24	2.1069	9.5
60-72	24.37	1.3994	5.7

A previous analysis of the data was performed in order to eliminate influential values. As suggested by Carvalho and Lima (2015) the data were evaluated in a temporal scale; following the minimum standards of uniformity and survival; besides considering only positive or null growth rates in the basal area of the plot of forest inventory.

Adjustment strategies and evaluated models

Two strategies of adjustment were evaluated in order to represent the height growth. The first strategy consists in the model adjustment with all the information, namely, including the early measurements, taken at 6, 12, 24, 36, 48, 60, and 72 months of age. The second strategy considers only the measurements of the continuous forest inventory that are traditionally performed in plantations of Eucalyptus, namely, excluding the measurements at 6 and 12 months, starting at the 24th month after planting.

The evaluated models were the non-linear Schumacher (Eq.1), Chapman-Richards (Eq.2), Logistic (Eq.3) models.

$$HT_i = exp(\beta_0 + \beta_1 I_i^{-1}) + \varepsilon_i \quad (1)$$

$$HT_i = \beta_0[1 - exp(\beta_1 I_i)]^{\beta_2} + \varepsilon_i \quad (2)$$

$$HT_i = \frac{\beta_0}{1+exp\left(\frac{\beta_1 - I_i}{\beta_2}\right)} + \varepsilon_i \quad (3)$$

In which: HTi = average of total height, in meters, of the i-th plot; Ii = age, in years, of the i-th plot; βk, = regression parameters; Ɛi = random error of the i-th observation.

Current Annual Increment obtained through the analyzed models

The influence of the forest inventories on the production curves was analyzed through the maximum current annual increment that reflects directly in the shape of the curves (Figure 5). The equations that represent the current annual increment in total height (CAI) were obtained through the first derivative of the Schumacher, Chapman-Richards, and Logistic models (Equations 4, 5, and 6, respective.

$$CAI = -\left[exp\left(\beta_0 + \frac{\beta_1}{x}\right)\left(\frac{\beta_1}{x^2}\right)\right] \quad (4)$$

$$CAI = -\{\beta_0([1 - exp(\beta_1 x)]^{(\beta_2-1)}[\beta_2 exp(\beta_1 x)\beta_1])\} \quad (5)$$

$$CAI = \beta_0 \left\{\frac{exp\left[\frac{(\beta_1 - x)}{\beta_2}\right]\frac{1}{\beta_2}}{1+exp\left(\frac{\beta_1 - x}{\beta_2}\right)^2}\right\} \quad (6)$$

In which “x” is the age of the measurement, in years.

The values of maximum CAI in total height were obtained through the maximization of Equations 4, 5, and 6 in both adjustment strategies proposed in this study. These procedures were implemented in the RStudio environment through the “optimize” function of the “stats” package.

Accuracy evaluation of the analyzed models

The accuracy of the models was analyzed through the statistics expressed by the equations 7, 8 and 9:

Root mean square error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}} \quad (7)$$

Akaike Information Criterion (AIC)

$$AIC = -2\ln(mv) + 2p \quad (8)$$

Bias (B)

$$B = \frac{\sum_{i=1}^{n} Y_i - \sum_{i=1}^{n} \hat{Y}_i}{n} \quad (9)$$

The evaluation of the residual dispersion measurement for each curve and adjustment situation proposed was carried out in addition to the statistical analysis.

Test of model identity

The similarity analysis between the curves, in the different adjustment strategies proposed, was done by running the test of model identity. This procedure was suggested by Graybill (1976) and commented by Regazzi (1996), in which the identity of the models is based on the comparison between the squared sum of the residuals of the complete models with and that of the reduced models. In this case, the reduced model was the one that contained only the inventory data after 24 months (strategy 2) and the complete model the one with the total data base, that includes the measurements of forests with 6 and 12 months of age (strategy 1).

Results and discussion

Adjustment analysis of the analyzed models

The Table 2 presents estimates of the parameters and their respective standard error values for each analyzed model and adjustment strategy (with and without the presence of the forest inventory with trees with ages from 6 to 12 months).

Table 2 - Parameter estimate and standard error (between parentheses) for the analyzed model.

Strategy	Model	β_0	β_1	β_2
1	Schumacher	3.4076 (0.0026)	-1.4141 (0.0062)	---
2	Schumacher	3.5283 (0.0064)	-1.8256 (0.0210)	---
1	Chapman-Richards	25.7715 (0.1014)	-0.6073 (0.0065)	1.8273 (0.0146)
2	Chapman-Richards	27.2023 (0.5165)	-0.4669 (0.0375)	1.3685 (0.1032)
1	Logistic.	22.8826 (0.0478)	1.8300 (0.0057)	0.6188 (0.0032)
2	Logistic.	25.8744 (0.2840)	1.8108 (0.0249)	1.3371 (0.0531)

Legend: 1 = with the data of the forest inventory of trees with 6 and 12 months; 2 = without the data of forest inventory of trees with 6 and 12 months

The low standard error values associated to the parameters indicate a good quality associated to the adjustments of the different models. In addition, this work shows that all the parameters were significant at 95% confidence level. Figures 1, 2, and 3 confirm the results of Table 2, in which the parameter models were tilled (Bolker, 2008) in order to assure the accuracy of the estimate of the parameters of each model, especially because they are non-linear functions.

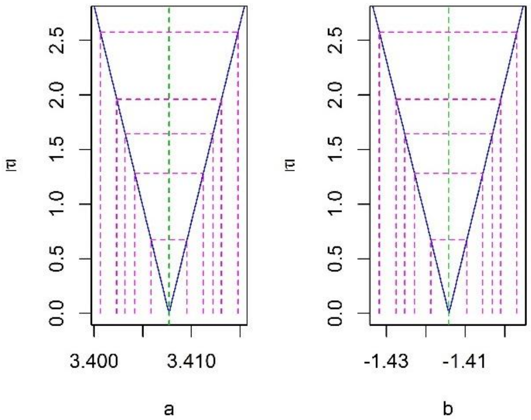

Figure 1 - Profile of Schumacher parameters.

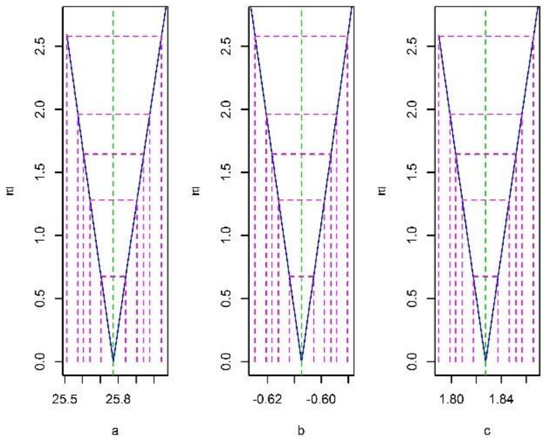

Figure 2 - Profile of Chapman-Richards parameters.

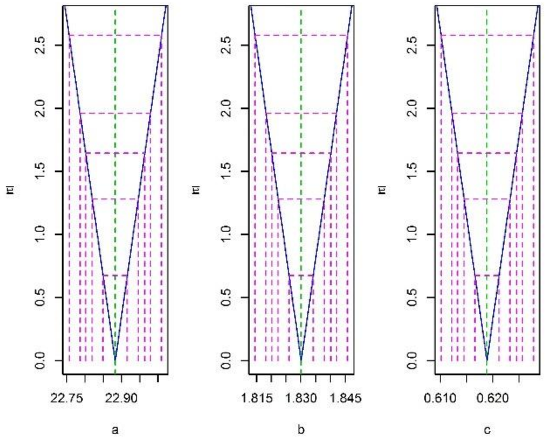

Figure 3 - Profile of Logistic parameters.

The Table 4 presents the statistics for the evaluation of the models under different adjustment strategies. They reveal that the adjusted analyzed models based on forest inventories with the presence of data from trees with 6 and 12 months (strategy 1), have generally obtained a higher accuracy compared to the adjusted data without these early data (strategy 2). The three adjusted models based on strategy 2 were more biased compared to those based on strategy 1.

Among the evaluated model, the Chapman-Richards model presented the highest accuracy. The results show that the measurement of plots at early ages (until 24 months) improves significantly the predictive quality of the model.

The residuals of the adjusted curves in the different adjustment strategies are represented in Figures 4 and 5.

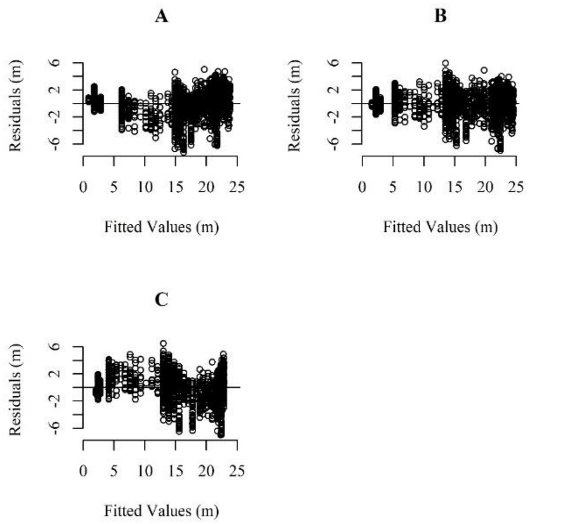

Figure 4 – Distribution of residuals of the different curves in each adjustment strategy with the inclusion of the forest inventories of trees with 6 and 12 months. A = Schumacher Model; B = Chapman-Richards Model; C = Logistic Model.

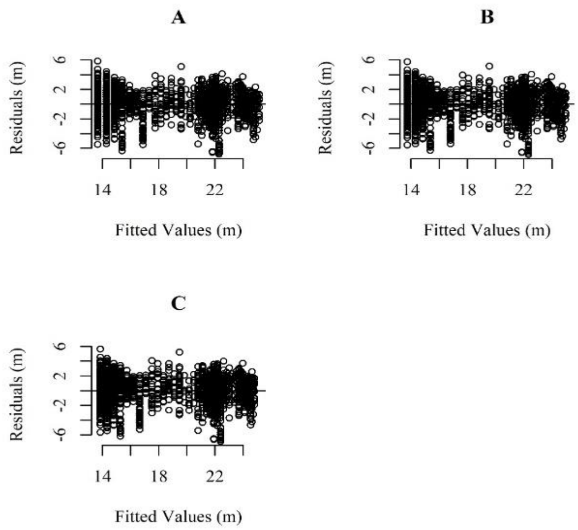

Figure 5 - Distribution of residuals of the different curves in each adjustment strategy with measurements of trees after 24 months. A = Schumacher Model; B = Chapman-Richards Model; C = Logistic Model.

Table 4 – Statistics to evaluate the accuracy of the analyzed model according to the proposed adjustment strategies.

Strategy	Model	RMSE (m)	AIC	B
1	Schumacher	1.35	20,120	30.82
2	Schumacher	1.85	7,944	316.01
1	Chapman-Richards	1.19	18,727	-1.50
2	Chapman-Richards	1.85	7,941	316.01

1	Logistic	1.33	19,951	-10.40
2	Logistic	1.85	7,939	316.00

The Chapman-Richards function presented the best dispersal of residuals from the line zero (Figure 4) when compared to the others, which exhibit trends. The best accuracy was obtained by the Chapman-Richards model due to the sigmoidal characteristics of the function, which describes with exceptional specificities the biological phenomena, in which the curve starts from "zero" in the dependent variable when the independent variable is also "zero" (Scolforo and Machado 1988; Raimundo et al. 2016; Pissinin and Schneider 2017). When the adjustment strategy that is evaluated removes information from trees with 6 and 12 months, there are no significant differences in the residual dispersions for the different evaluated functions.

Height growth curves for the models according to the adjustment strategies

The Figure 6 shows the different tendencies for the models with or without the presence the inventories with trees with ages of 6 and 12 months.

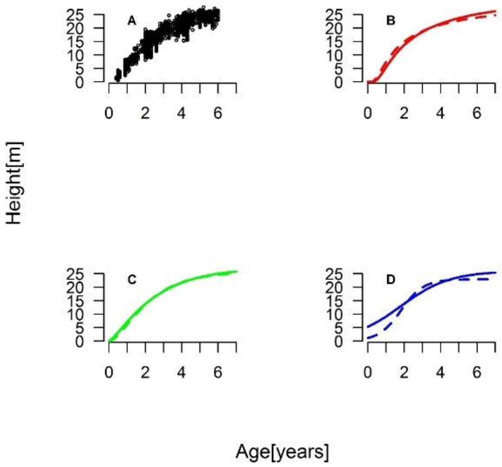

Figure 6 – Growth tendencies observed by the different functions evaluated in this study. A = field measured data; B = Schumacher Model; C = Chapman-Richards Model; D = Logistic Model. The dashed line refers to the results of strategy 1 and the full line represents the adjustment made using strategy 2.

The Figure 6 shows that the Logistic model was the most sensitive to the strategies of adjustment (presence or absence of measurements at 6 and 12 months). This was able to be checked when the estimates of the parameters of this model were analyzed (Table 2). According to Calegario et al. (2005) and Mendonça et al. (2017), in the logistic model, the parameter β_0 represents upper horizontal asymptote (UHA), that is, the maximum value of the response (H) in time (I). The parameter β_1 represents the point of inflection of the curve, namely, the age (I) in which the production (H) reaches half of the β_0. And, the parameter β_2 (scale) represents the difference between the age where production reaches approximately 73% of β_0 and the age of the point of inflection. The adjustment of this model by strategy 1 resulted in a lower UHA estimate than by strategy 2. The estimates of the point of inflection of the curve were similar in both adjustment strategies. In the estimate of the scale, by its turn, the strategy 1 resulted in a higher value than strategy 2. For the other models, there was no notable visual difference between the adjustments according to the analyzed strategies, especially for the Chapman-Richards models, making it the best choice.

The results of the test of model identity (Table 3) allow us to infer that there a significant difference in the adjustment of the growing models with and without of the initial measurements of the planting (6 and 12 months), corroborating the results exhibited in Table 4 and Figure 6.

Table 3 – Similarity analysis of the curves by means of the test of model identity.

Model	**Test Significance (table value)**
Schumacher	3972.4 (0.2965*)
Chapman-Richards	1727.9 (0.1292*)
Logistic	3690.2 (0.2763*)

In which: * = significant (p>0.01)

The early ages (lower than 12 months) are generally little used in the forest environment for modeling growth and production, since they commonly present the larger variation of growth. Factors like site, planting density, and genetic material affect the homogeneity of monoclonal populations of Eucalyptus (Soares et al. 2016) and consequently in the accuracy of the growth modeling. In some cases, and species like Mimosa scabrella and Tectona grandis, studies recommend the non-utilization of early ages in the data bank used for modeling height growth (Machado et al. 1997; Chaves et al., 2016). However, the results of these investigations show that for Eucalyptus populations, the insertion of information about the planting in the early ages promoted a significant gain in the modeling and, consequently, in the precision of these functions. Further, it is important to mention that the genetic material may be a conditioning constraint for these results, since according to Hakamada et al. (2015) the clonal populations tend to exhibit a higher growth, production, height uniformity in the trees.

The different points of maximum current annual increment (CAI) for the different models and strategies of adjustment are shown in Figure 7. It shows that the Schumacher and Chapman- Richards models exhibited a change in the age of maximum CAI in height with the use of early inventories (strategy 1). For the Logistic model, the use of data from these inventories did not result in different ages of CAI in height, but the value of the increment in the age the maximum CAI was higher when comparing the adjustment data for strategy 2.
The option for one of the models may result in differences of production of up to 48%, as observed in the Chapman-Richards function. Their maximum points were respectively of 0.99 years (full line) for the adjustment with the measurements of 6 and 12 months, and of 0.67 years (dashed line) when this information was not taken into account. This shows the importance of different models for each new data bank. The Chapman-Richards function is among the most used functions in the forest environment, because it has characteristics that in most cases provide good results (Ferraz-Filho et al., 2011; Lima-Filho et al., 2012). Its flexibility enables the identification of height differences in the production when the data of the early inventory are used, and this may provide the basis for silvicultural actions in fast growing populations.

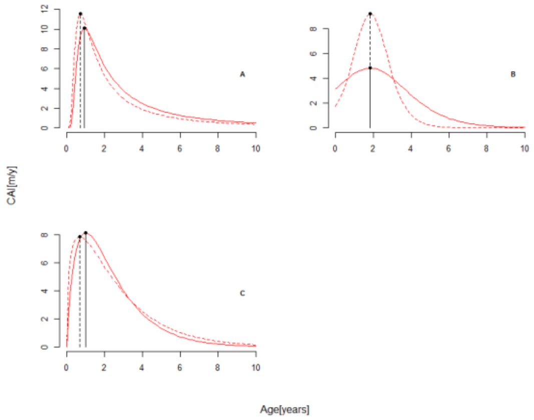

Figure 6 – Production Curves for the different contexts and evaluated functions. (A) Schumacher, (B) Logistic, (C) Chapman-Richards

Conclusions

Regardless of the type of adjustment, the Chapman-Richards model was the most precise.

There was an accuracy gain when data from the forest plantation inventory at 6 and 12 months were used in the models of height growth of monoclonal populations of Eucalyptus spp.

Considering the shapes of the growth and production curves, there is a significant effect of the initial measurements in the shape of the three models analyzed in this study.

The results found in this investigation will provide information to the forest manager about the purpose of the production functions, both in the statistical and in the practical approaches, implying therefore in the stability of the model and in its adherence to the data.

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