Forest Ecology and Management 408 (2018) 36–44

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Site index curves in thinned and non-thinned eucalyptus stands

Gabriela Cristina Costa Silva[a,*], Natalino Calegario[b], Antonilmar Araújo Lopes da Silva[a], Jovane Pereira da Cruz[a], Helio Garcia Leite[a]

[a] Federal University of Viçosa, Department of Forestry, Campus Universitario, CEP36570-000, Viçosa, MG, Brazil
[b] Federal University of Lavras, Department of Forestry, Campus Universitario, CEP 37200-000, Lavras, MG, Brazil

ARTICLE INFO

Keywords:
Guide curve method
Chapman-Richards
Non-linear model
Longitudinal data
Polymorphism

ABSTRACT

The aim of this study is to compare different non-linear models in order to classify the productive capacity of thinned and non-thinned eucalyptus stands by using the guide curve and longitudinal measurement modeling methods of the height of dominant and co-dominant trees, in different sample units and site potential. The Schumacher, Chapman-Richards, logical, Gompertz, and Bailey-Clutter models are tested in the guide curve method. These models are compared using statistics for residual standard error (Sy.x) and percentage (Sy.x%), Akaike information criteria, Bayesian information criteria, and the consistency observed between site index curves as well as the observed dispersion of the dominant heights. In addition, at the base without thinning, conformation of the data is observed using the Schumacher model based on dominant height groups at the reference age (84 months). Moreover, we conduct a comparison of the parameters based on the Z test. The Chapman-Richards model most effectively adjusts to the two data sets (i.e., those with and without thinning) and produces curves that best reflect the behavior of the dominant height variable. Thinning at the base does not affect dominant height growth, and no polymorphism is observed between the curves of the groups. The range of the site classes defined by the proposed method may be more suitable for differentiating the productive classes.

1. Introduction

With advanced techniques for managing even-aged stands, increasing the variety of products obtained from these plantations, including from different segments of a forest area, has become possible. Choosing a purpose for the plantation directly affects the management techniques adopted, such as avoiding or not the use of thinning, in order to obtain one or more final products having characteristics desirable to the consumer (Alves et al., 2015).

Distinguishing between the regimes to be adopted in each forest area depends on edaphic, climatic, and physiographic conditions as well as productive aims. Therefore, evaluating the risks and consequences of managing a stand for a determined purpose in order to outline the most adequate guidelines to achieve intended productivity is critical.

To define the best regime for integrated management, understanding the productive capacity of each location is necessary. This productive capacity is defined as the potential to produce wood of a determined species based on environmental factors (edaphic, climatic and physiographic), genotype and forestry practices. The determination of the productive capacity can be carried out in a quantitative manner, generating a site index that is used as input in models for prognosis of growth and forestry production.

Classifying this productive capacity can be accomplished using indirect or direct methods. Indirect methods are based on physiographic, climatic, and edaphic characteristics of the location, whereas direct methods are based on stand measures such as volume or height (Clutter et al., 1983). In the latter, the site index defined by the dominant height (hd) is the most commonly used measure. This is because the site index correlates well with production and is a variable unaffected by stand density (Burkhart and Tomé, 2012). It is worth noting that the hd is not affected by plantation density within a commercial range. Extreme density values affect hd, as do other biometric forestry variables.

Direct classification by dominant height is conducted by using the site index curves. These curves are constructed based on the functional relation hd = f(age). Using exponential or sigmoid models for this purpose is common. Different methods exist for constructing site index curves (Campos and Leite, 2017), with the guide curve method being the most common (Miguel et al., 2011; Pego et al., 2015; Retslaff et al., 2015). In Brazil, index curves of anamorphic sites have been most commonly employed. However, in certain cases, polymorphism can be found using the more suitable polymorphic curves. Therefore, when

* Corresponding author.
E-mail addresses: gbcristina.silva@gmail.com (G. Cristina Costa Silva), calegari@dcf.ufla.br (N. Calegario), antonilmar.silva@cenibra.com.br (A. Araújo Lopes da Silva), jovanecruz@gmail.com (J. Pereira da Cruz), hgleite@gmail.com (H. Garcia Leite).

http://dx.doi.org/10.1016/j.foreco.2017.10.036
Received 22 July 2017; Received in revised form 17 October 2017; Accepted 19 October 2017
0378-1127/

classifying productive capacity, verifying whether polymorphism indicators exist is important. The objectives of this study are to compare different non-linear models for classifying the productive capacity of thinned and non-thinned eucalyptus stands by using the guide-curve and longitudinal measurement modeling methods for dominant and co-dominant tree height in different sample units and potential sites, as well as to verify the presence of polymorphism.

2. Methodology

2.1. Description of data

For this study, a first longitudinal data set (measured over time) was obtained in permanent plots of continuous forestry inventories. The eucalyptus stands are located in the municipality of Virginópolis in the Central Eastern region of Minas Gerais, Brazil. The climate of the region is Cwa type, which is a climate consisting of a dry winter and rainy summer. The temperature of the coldest month is below 18 °C and the hottest is above 22 °C. The geography of this region is considerably undulating and includes many rocky outcroppings. The predominant soils are latosols and cambissols. The region is located at a latitude of 18°49′5″ South and a longitude of 41°41′46″ East with an altitude of 743 m. The stand was planted in April 2003 and managed in a high stem regime, with initial spacing of 3.0 × 3.0 m^2. The measurements of the plots were conducted in 2006 and 2013, where 295 rectangular plots were measured with approximately 300 m^2 of area in ages of 3–8 re-measurements. The approximate sample intensity was 1:10 (one plot every 10 hectares).

A second data set was obtained from a thinning experiment conducted in northeast Bahia in hybrid stands of *Eucalyptus urophylla* × *Eucalyptus grandis*. established in September 1995 when the stands were 27 months old. This experiment was conducted in three locations: Bonfim (11°52′ S and 38°32′ W, at 285 m altitude having 900 mm of average annual rainfall); Tombador (12°03′ S and 38°28′ W, at 290 m altitude having 1100 mm of average annual rainfall); and Lagoa do Bu (11°47′ S and 37°55′ W, at 150 m of altitude having 1200 mm of average annual rainfall). The plots were in a 2600 m^2 area and the initial spacing was 3.5 × 2.6 m^2. The design was in randomized blocks, with two blocks per site and two repetitions per block.

The evaluated treatments involved removing basal area present at thinning age, with 20 (T1), 35 (T2), 50 (T3), and 35% more artificial pruning to a height of 6.0 m (T4). The first thinning was conducted at 58 months of age, and the second at 142 months, with the smaller trees being removed. The variables measured for each plot and age were: diameter at 1.30 m high in all trees, total height of the first 15 normal trees, and the height of the five dominant trees. Additional details regarding the experiment can be found in Campos and Leite (2017), Nogueira et al. (2015) and Dias (2005).

The methods and analyses presented in the following sections were applied to the data regarding the stands managed with and without thinning.

2.2. Classification of productive capacity

Classification of the productive capacity was conducted using the direct method and by constructing site index curves. The guide curve method was used to assess the adjustments to the Schumacher, Chapman-Richards, logical, Gompertz, and Bailey-Clutter non-linear statistical models (Table 1).

For all adjusted models, six anamorphic curves that organize the data into three site classes were generated for an age index of 84 months. The adjustments and other statistical analyses were performed using the *software* R and Microsoft Excel.

Table 1
Models tested for estimating the dominant height and for classifying the productive capacity of eucalyptus stands, with and without the application of thinning at the base.

Model	Statistical model	Function of site index
Schumacher	$\overline{H}DC_i = \varnothing_0 e^{\left(\varnothing_1\left(\frac{1}{I_i}\right)\right)} + \varepsilon_i$	$S = \overline{H}DC_i e^{\left[\hat{\varnothing}_1\left(\frac{1}{I_{ref}} - \frac{1}{I_i}\right)\right]}$
Chapman-Richards	$\overline{H}DC_i = \varnothing_0(1-e^{(\varnothing_1 I_i)})^{\varnothing_2} + \varepsilon_i$	$S = \overline{H}DC_i\left(\frac{1-e^{(\hat{\varnothing}_1 * I_{ref})}}{1-e^{(\hat{\varnothing}_1 * I_i)}}\right)^{\hat{\varnothing}_2}$
Logical	$\overline{H}DC_i = \frac{\varnothing_0}{1+e^{\left(\frac{\varnothing_1 - I_i}{\varnothing_2}\right)}} + \varepsilon_i$	$S = \overline{H}DC_i \frac{1+e^{\left(\frac{\hat{\varnothing}_1 - I_{ref}}{\hat{\varnothing}_2}\right)}}{1+e^{\left(\frac{\hat{\varnothing}_1 - I_i}{\hat{\varnothing}_2}\right)}}$
Gompertz	$\overline{H}DC_i = \varnothing_0 e^{-e^{(\varnothing_1 - \varnothing_2 I_i)}} + \varepsilon_i$	$S = \overline{H}DC_i \frac{e^{-e(\hat{\varnothing}_1 - \hat{\varnothing}_2 * I_{ref})}}{e^{-e(\hat{\varnothing}_1 - \hat{\varnothing}_2 * I_i)}}$
Bailey-Clutter	$\overline{H}DC_i = \varnothing_0(1-e^{\varnothing_1 I^{\varnothing_2}}) + \varepsilon_i$	$S = \overline{H}DC_i \frac{(1-e^{\hat{\varnothing}_1 * I_{ref}^{\hat{\varnothing}_2}})}{(1-e^{\hat{\varnothing}_1 * I_i^{\hat{\varnothing}_2}})}$

2.3. Statistical analysis of the HDC estimates

Evaluation of adjustments was conducted using residual standard error estimates (1) and percentages (2); Akaike information criteria (3) based on Sakamoto et al. (1986); Bayesian information criteria (4) based on Schwarz (1987); and the consistency observed between the site index curves as well as the observed dispersion of the dominant and co-dominant heights.

$$Sy.x = \sqrt{\frac{\sum_{i=1}^{n}(y-\hat{y})^2}{n-p-1}} \quad (1)$$

$$Sy.x(\%) = 100\frac{Sy.x}{\hat{y}} \quad (2)$$

$$AIC = -2\ln(mv) + 2p \quad (3)$$

$$BIC = -2\ln(mv) + p\ln(n) \quad (4)$$

where *Sy.x* = residual standard error (m), *Sy.x* (%) = relative standard error (%), y = observed dominant height, $\hat{y}$ = estimated dominant height, n = number of observations, p = number of parameters in the model, mv = maximum likelihood value, and ln = Nepierian logarithm.

With the plots classified based on the rearranged models, the stability test for each equation was realized by considering the number of times that the plots changed classification over time. For this analysis, only those plots included in the curves over the entire period of measurement were used.

2.4. Classification of productive capacity for modeling the longitudinal trajectory of data for dominant and co-dominant average height

With the aim of verifying the polymorphism of the data, we propose an analysis in which the Schumacher model was used, an exponential asymptotic model (i.e., one that effectively represents the behavior of the Hd = f(age) relation). The model is also parsimonious (includes fewer variables), which facilitates interpretation.

Modeling of the longitudinal trajectory was applied only to the data of the non-thinned stands. The Schumacher model was adjusted for data subsets (groups), which were defined according to the dominant and co-dominant heights observed at an age of approximately 84 months (reference age). Four groups were defined: for dominant heights varying from 20 to 25 m (group 20), 25.1 to 30 m (group 25), 30.1 to 35 (group 30) and 35.1 to 40 (group 35).

In order to define a sufficient number of plots to develop this analysis, the sampling sufficiency for each group was calculated at an admissible sampling error of 5% (5).