Forest Ecology and Management 380 (2016) 182–195

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Modeling dominant height growth of eucalyptus plantations with parameters conditioned to climatic variations

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ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form 31 August 2016
Accepted 4 September 2016

Keywords:
Precipitation
Clear-cut
Coppice
Brazil

ABSTRACT

Dominant height growth equations, which given at some base age is defined as site index, is usually used to assess site quality. A flexible and accurate way to represent the potential productive capacity of forest stands of *Eucalyptus* spp. was developed. The generalized algebraic difference method was used, in which 15 dynamic equations were tested for modeling dominant height growth. The models were fitted to a data set derived from permanent plots located in the states of Bahia (BA) and Espirito Santo (ES), Brazil, with clonal eucalyptus plantations. The database was analyzed separately for the clear-cut and coppice regimes. The selection of the best-fitting model for each management regime was based on statistical fitting, predictive validation, and graphical analysis. After selection of the best model, one of its parameters were expanded with the addition of climatic variables that allowed for the creation of scenarios. The polymorphic modified Von Bertalanffy-Richards model with a single asymptote performed the best for the two management regimes. For clear-cut management, conditioning the slope parameter by the mean monthly precipitation obtained the best performance. For coppice management, the asymptote parameter conditioned by the mean monthly precipitation and its distribution throughout the year provided the best performance. The inclusion of the climate modifiers added flexibility for the models, which was represented by the interannual variations of precipitation. Expansions of the parameters did not mischaracterize the behavior of the modified Von Bertalanffy-Richards model for the management regimes studied. Climatic conditioning of the parameters of the slope and asymptote for the two management regimes led to accuracy gains in the estimates. Additionally, this enabled the generation of productivity scenarios based on the amount and distribution of the total precipitation for the areas under study.

1. Introduction

The area of planted forests in the world is equivalent to 264 million hectares. Of this total, 61% of the forest stands are located in China, India, and the United States. In Brazil, the plantations of *Eucalyptus* and *Pinus* sp. reached 7.60 million hectares in 2013, with 71.2% of this being plantations of *Eucalyptus* sp. Brazil contributes 17% of the total timber harvested in the world, much of it due to the high productivity of its forests, especially those of the eucalyptus genus (IBÁ, 2014).

Brazilian timber is used as raw material for the production of pulp, paper, wood panels, solid products, coal, industrial wood, treated wood, and wood chips; however, pulp is the product of greatest interest. Among the Brazilian states, 15.5% of the eucalyptus forest stands established for pulp production are located in the states of Bahia (BA) and Espirito Santo (ES) (IBÁ, 2014). In 2014, the forestry sector accounted for 1.1% of the Brazilian GDP and 5.5% of its industrial GDP (Cirillo, 2015). Due to this importance to the national economy, there is a need to periodically monitor forest stands as a way of fostering information for planning and

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http://dx.doi.org/10.1016/j.foreco.2016.09.001
0378-1127/© 2016 Published by Elsevier B.V.

decision-making of a strategic, tactical, and operational nature (Guedes et al., 2012).

This periodic monitoring is performed by means of sample delineations that efficiently capture the changes in forest stands over time. Sampling consists of a network of permanent plots, and the procedure is known as Continuous Forest Inventory (CFI), which provides information regarding stock and annual growth (Mello et al., 2009). CFI information is fundamental for the building of mathematical models that, by forecasting future timber production, are a key to guiding forest planning. In this context, the classification of the potential productive capacity or site index of different plantation locations is the key to the process (Pokharel and Dech, 2011).

Timber prognosis in forest stands can be performed in two different ways, which derive from different philosophies of the tree growth. The first is based on ecophysiological principles in which a conceptual model is used to identify the cause and effect factors in biomass production. The second approach is called descriptive and aims to identify and describe the patterns of growth and production for the management practices of forest resources (Burkhart and Tomé, 2012). The descriptive method of predicting timber production is based on the dendrometric data from CFI; that is, it is based on repeated measurements for making estimates of growth. The sampling intensity enables inference per plot or set of plots with the same characteristics to guide medium - and long-term forest planning. An overview of forest site productivity assessment can be found in Skovsgaard and Vanclay (2008). In addition Burkhart and Tomé (2012) provide detailed coverage of methods for even aged stands.

The combination of the second approach with climate variables can provide greater information accuracy, given that it can fill in the gaps of descriptive models, which are not sensitive to interannual climatic variations (Scolforo et al., 2013). Ferraz-Filho et al. (2011) and Scolforo et al. (2013) studying *Eucalyptus grandis* in southeastern Brazil showed that combining descriptive models with climate variables facilitates the application and understanding by forest users. Since, descriptive models have been used to describe the patterns of growth and production for forest management practices, these authors claimed that this approach would be an useful tool for updating forest inventory in the short term while accounting for climate variation. Combining descriptive models to climate variables has been applied with success in site classification, as shown by González-García et al. (2015), where the authors predicted site index for *Eucalyptus nitens* and found appropriate results when applying the fitted function for areas without inventory information.

Remy de Perthuis de Laillevault, in the 18th century in France, was the first author to assess site quality by height growth (Batho and García, 2006). Subsequently, using dominant height of trees of the stand became popular to assess site quality. The concept of site index to assess site quality was first introduced for species with long rotations (Alemdag, 1991). Probably the most recognized technique to site index modeling was developed by Bailey and Clutter (1974), where the authors presented and applied the idea of dynamic, base age invariant equations for *Pinus radiata* in New Zealand. This approach was later generalized by Cieszewski and Bailey (2000). These dynamic equations are commonly used to compute predictions directly from any age-height pair, excluding the needs to incorporate the climate effect. Several successful examples of using these approaches are reported in the literature, including, Monserud (1984) and Diéguez-Aranda et al. (2005).

In the late 1990s, authors such as Woollons et al. (1997), started to include climatic variables in the classical dynamic equations. The authors, however, found no significant improvement by incorporating climatic variables in analyses for *Pinus radiata* in New Zealand. Bravo-Oviedo et al. (2008) and Nunes et al. (2011) studying *Pinus pinaster* Ait in Spain and Portugal, respectively, also related dominant height growth to climate variables. These authors concluded that inserting climate variables in the site index equations provided an improvement of the estimates by increasing efficiency on a regional scale and reducing bias.

Although regional climate differences have been incorporated in some studies, interannual climatic variation also has a great impact on the development of Brazilian eucalyptus cultivation (Stape et al., 2004). For example, considering a rotation of seven years for a eucalyptus stand, a dry period in one of the years can dramatically affect its final yield (Almeida et al., 2004). In other words, after data collection and model update, the observed pattern of climatic variation is key to understanding forest growth in following years.

Thus, the development of accurate tools that are also sensitive to these variations has great potential for use in the classification of the potential production capacity for eucalyptus in Brazil, as responsiveness to changes in climate is essential for the production of plantations, due to the short rotation. Therefore, an approach of incorporating climatic variables in the descriptive models used for classification of the potential productive capacity of eucalyptus plantations in Brazil is necessary—a model country in the production of rapid-growth timber but which has a gap in the observation of mechanisms for understanding impacts on the growth of forest stands caused by the climate. The addition of interannual climatic variation allows the insertion of sensitivity into mathematical models. Additionally, this sensitivity in the model allows forest managers to assess the impact on local climate variability, either for the full rotation or for 1 year ahead. This feature is important for enabling more accurate planning.

The objectives of this study were to represent the potential productive capacity (site index) of a eucalyptus clone located in the states of Bahia and Espirito Santo; increase the performance of the descriptive model via climatic variables; and generate productivity scenarios in accordance with possible interannual climatic variations.

2. Materials and methods

2.1. Physiographic and socio-economic characterization of the study area

The eucalyptus stands are located in the states of Bahia (BA) and Espirito Santo (ES), with latitude ranging from 17°15′S to 20°15′S and longitude from 39°05′W to 40°20′W. BA is located in the northeast region of Brazil and is the fifth largest by area, the fourth most populous, and has the eighth largest GDP in Brazil (3.8% of national GDP). ES is located in the southeast region of Brazil and is the fourth smallest by area, the fourteenth most populous, and has the eleventh largest GDP in Brazil (2.4% of national GDP) (IBGE, 2014). To get an idea of the size of these states, the sum of their areas exceeds the area of France and Belgium together.

The area's climate classification, in accordance with the Köppen classification, ranges from Aw (tropical climate with precipitation greater than 1500 mm and dry winter) to Cwb (humid subtropical climate with dry winter and temperate summer) in ES and Af (tropical climate without dry season with mean air temperature above 18 °C) in BA (Alvares et al., 2013). In accordance with the climatic conditions in BA and ES and, more specifically, in the study area, there is climatic similarity but with a significant precipitation difference.

2.2. Sampling and data acquisition

The database was composed of forest inventory data derived from the CFI as well as climatic data from weather stations. The