Forest Ecology and Management 391 (2017) 145–153

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Incorporating rainfall data to better plan eucalyptus clones deployment in eastern Brazil

Henrique Ferraco Scolforo [a,*], Jose Roberto Soares Scolforo [b], Jose Luiz Stape [a,c], John Paul McTague [a], Harold Burkhart [d], James McCarter [a], Fernando de Castro Neto [b], Rodolfo Araújo Loos [e], Robert Cardoso Sartorio [e]

[a] Department of Forestry and Environmental Resources, North Carolina State University, 2820 Faucette Dr., Campus Box 8001, Raleigh, NC 27695, United States
[b] Department of Forest Science, Federal University of Lavras, Campus Universitario, Campus Box 3037, LEMAF, Lavras, Minas Gerais 37200-000, Brazil
[c] Department of Forest Science, University of São Paulo, Av. Padua Dias 11, 13418-900 Piracicaba, São Paulo, Brazil
[d] Department of Forest Resources and Environmental Conservation, Virginia Polytechnic Institute and State University, 310 W Campus Dr, Campus Box 169, 24061 Blacksburg, VA, United States
[e] Fibria Celulose S.A. Rod. Aracruz, B. Riacho, Aracruz 29192-000, Brazil

ARTICLE INFO

Article history:
Received 22 December 2016
Accepted 10 February 2017
Available online 23 February 2017

Keywords:
Site index
Coppice
Clear-cut

ABSTRACT

The goals of this study were to identify and group three eucalyptus clones, each under coppice and clear-cut management regimes, into two or more groups based on similar growth rates; and fit a site index equation as a function of rainfall variables for each group to evaluate how different groups were impacted by climatic variation. The database came from the Continuous Forest Inventory (CFI) and weather stations. The CFI was conducted between 1994 and 2012, with climatic data also being gathered for the same period. The study area was managed by clear-cut and coppice regimes, with 126 and 72 CFI plots, respectively. The relationship between clones, management regimes and stand age with annual dominant height growth was assessed by linear mixed effects modeling. Ridge regression was applied for fitting each group as a function of the rainfall variables. Finally, ordinary Kriging was applied for each of the rainfall variables in the study area. Then, site index equations were applied to the generated maps enabling the observation of their pattern throughout the study area as well as their evaluation under a pessimistic climatic scenario. Three groups were defined, since each clone exhibited similar growth behavior under either management regimes; however, the 3 clones differ among each other. A significant reduction in the annual dominant height growth over time was observed for all 3 clones. Ridge regressions afforded good accuracy and equations with sound biological behavior. Applying the fitted site index equations to the maps of precipitation and rainy days enabled the definition of the most appropriate clone to be planted throughout the area. Site quality as a function of rainfall variables could be an important tool to better enable silvicultural planning, since it provides estimates of the site index and also enables the incorporation of short-term climate change.

1. Introduction

A total of 7.60 million hectares of plantation forests, including 5.41 million hectares of *Eucalyptus* spp., were established in Brazil by 2013 (IBÁ, 2014). One major advantage of eucalyptus forests is their rapid growth rate, which is well known for being the highest in the world among hardwood forests (Myburg et al., 2014). Campinhos (1999) reported that the mean annual increment (MAI) for a eucalyptus forest averaged 12 m^3/ha/year in 1960s. Nowadays, as emphasized by Stape et al. (2010), eucalyptus production has dramatically increased, with MAI in the range of 20–60 m^3/ha. This increased growth rate is the result of intensive silviculture, breeding techniques and improvement of genetic materials (Stape et al., 2010).

The states of Bahia and Espírito Santo have 15.5% of the eucalyptus plantations in Brazil. These two states represent an area greater than France and England combined, and they are located in the subtropical zone of Brazil. For this Brazilian sub-region, considerable attention has been extended to develop breeding programs for *Eucalyptus grandis* (Myburg et al., 2014). In addition, cross breeding this species with *Eucalyptus urophylla* has increased

---

* Corresponding author.
E-mail address: henriquescolforo@hotmail.com (H.F. Scolforo).

http://dx.doi.org/10.1016/j.foreco.2017.02.025

productivity and wood quality (Lemos, 2012). Although several commercial clones have been developed under clear-cut regimes (Gonçalves et al., 2013), and management of the sprouting (coppice) (Gonçalves et al., 2014), no specific study has addressed the grouping of clones (clones with similar growth rates). Ferraz Filho (2013) used dominant height growth in stands with low mortality to start addressing this question, although his main focus was to evaluate different initial spacing and thinning intensity for eucalyptus plantations in Brazil.

According to Almeida et al. (2004), climate change plays an important role in eucalyptus stands. The authors commented that since this species is managed on short rotations (5–7 years), a dry period during its rotation may dramatically decrease its yield. Especially for the eastern section of Brazil, Stape et al. (2004) indeed noticed a great impact in the production of eucalyptus stands caused by precipitation variation, which according to the authors was most correlated with eucalyptus growth.

Defining groups of clones and their response to climate variation is important for improvements in site specific management. Sabatia and Burkhart (2014) suggested a site index function based on biophysical variables to address the impact of climate variation on forest growth, but this function also could be used to identify the less susceptible and most appropriate group to be planted. Since eucalyptus plantations for traditional areas in Brazil do not show much random mortality, site index has the ability to describe the current potential capacity of the areas to produce timber (Skovsgaard and Vanclay, 2008) under climate change. Monserud et al. (2008) applied this approach to describe changes in site index for lodgepole pine in Canada. Scolforo et al. (2016a) predicted site index as function of climate variables and site characteristics. The authors reported that in addition to its utility, this function has the ability of predict and consequently indicate the best groups of clone for regions where there are no forests. However, this approach has to be used carefully and only for regions encompassing the range where data have been collected.

The development of tools that are sensitive to climate variation has great potential for use in Brazil. The development of models for not only making accurate estimates, but that permit forest managers to assess the impact on local productivity by climatic variation, would represent a great step forward the Brazilian forestry. This study: (1) identified and grouped three eucalyptus clones, each under coppice and clear-cut management regimes, in two or more groups based on similar growth rate; (2) fitted a site index equation as a function of rainfall variables for each group; and (3) evaluated how different groups are impacted by climatic variation, defining then the best groups to be planted throughout the selected areas.

2. Material and methods

2.1. Characterization of the study area and database

The states of Bahia and Espírito Santo are important for the Brazilian forestry sector. Bahia is located in northeastern Brazil and is the fifth largest state in the country, while Espírito Santo is located in southeastern and is the fourth smallest (IBGE, 2014). A climatic gradient exists from one state to another, and according to Alvares et al. (2013) rainfall distribution is the most significant variable related to climatic variation. The Köppen classification system for the Espírito Santo ranges from Aw to Cwb. The Aw is characterized as a tropical climate with precipitation greater than 1500 mm with dry winter, while the Cwb has a humid subtropical climate with dry winter and temperate summer. For Bahia, the Köppen classification is Af, characterized as a tropical climate without a dry season with mean air temperature above 18 °C. We divided the study area by climate regions, which are defined as BA – Af, ES1 – Cwb and ES2 – Aw.

Plots of three different eucalyptus clones were installed across the Bahia and Espírito Santo states in order to investigate their growth from ages 1 to 6 years under different management regimes (clear-cut and coppice) and climatic conditions. Continuous forest inventory (CFI) measurements were conducted from 1994 to 2012, where the 500 m^2 plots were systematically distributed throughout the area. Dominant heights based on the mean top height concept (Assmann, 1970) were measured. A total of 126 and 72 plots were installed and measured for the clear-cut and coppice management regimes, respectively. The three clones presented low mortality and were well distributed in the study area for both clear-cut and coppice management regimes. They were also well distributed in all the climatic zones (Fig. 1). The descriptive statistics for the clones are presented in Table 1.

The climatic data was obtained from 31 weather stations. Daily values for precipitation, Rainy days (number of days with rainfall exceeding 1 mm) and temperature (minimum, mean and maximum) were taken during the same observation period as the CFI measurements. Table 2 contains the summary statistics for the climatic variables in the study area. Precipitation and its distribution throughout the year (rainy days) showed greater variability when compared to the other variables.

The soils for the study area are predominantly Yellow Argisol (97% of the plots) with few places presenting Gleysol (3% of the plots). The Yellow Argisol is moderately deep and well drained, with the presence of a textural B horizon, while the Gleysol does not present a B horizon. In addition, there is variation with respect to elevation, however, the study region is characterized by low and flat lands, i.e., elevations ranging from 9 to 114 m above the sea. Elevation was extracted from the Digital Elevation Model (DEM).

2.2. Grouping the clones

Since there are three different clones across the landscape, each under two-management regimes, defining groups of clones with similar growth rate becomes important to stratify the dataset to potentially improve decision making for geneticists and silviculturists. The grouping may help differentiate the clones that differ from each other and define the impact of different management regimes on their resulting growth.

The three clones were planted under clear-cut and coppice management regimes and throughout the study area ranging across all the climatic zones and soils. Our goal was to determine the effect of the clone and management regime in forest plantations. We examined if different management regimes, clonal genetics, and stand age are impacting the annual dominant height growth. The study area did not include catastrophic mortality, so a measure of site quality indicates which stands have greater capability for timber production.

To establish the effects of the clones, management regimes, and the stand age on tree size, all of the plot measurements were utilized. A model, described by Ferraz Filho (2013), was formulated to test for variation on mean annual tree dominant height growth with respect to clones, management regimes and stand age. This model facilitates the grouping of clones with similar growth rates.

$$id_{lj} = \beta_0 + \beta_1 GM + \beta_2 M + \beta_3 Age + u_i + e_{ij} \quad (1)$$

where *id* is the mean dominant height growth for every plot throughout the measurements (m per year); GM is a factor variable for the genetic material/clone; M is a factor variable for management regime; *Age* is a variable for the stand age in years. Subscripts *i* and *j* refer to plot and tree, respectively; u_i and e_{ij} are iid with mean 0 and constant variances of σ^2_{plot} and σ^2, respectively.