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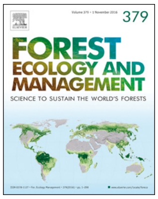

Yield pattern of eucalypt clones across tropical Brazil: An approach to clonal grouping

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ABSTRACT

The research objective of this paper was to group eleven widely planted eucalypt clones based on their volume yield pattern by assessing how climatic variation impacts their productivity in tropical Brazil. A total of 187 plots evenly distributed across eleven clones and 17 sites (from Paraná to Pará State) were used. Plot measurements were carried out every six months (from 2013 to 2017) to evaluate eucalyptus growth. Since the year of plot establishment differs across the sites, volumes of all the plots and sites were standardized at a common age of 5 years. Clonal grouping analysis was performed based on the common age for volume yields using a new approach, which consisted of three steps: (1) create general groups based on testing of the slope coefficient, which was applied to every clonal-specific regression with volume yield as a function of annual water deficit index (WDI); (2) split each general group using volume yield deviation computations into subgroups of high and low productivity; (3) apply linear mixed effects models for every subgroup in order to confirm the non-existence of statistical difference among the volume yield of the clones. Statistical tests showed satisfactory yield estimates at the common age of 5 years. Clonal grouping revealed the identification of four groups (A: high productivity and non-sensitive to climate variation, B: high productivity and sensitive to climate variation, C: low productivity and sensitive to climate variation, D: low productivity and non-sensitive to climate variation). The volume yield of the Clonal group B was detected to be the most impacted by annual water deficit index variation, followed by clonal groups C, A and D. The findings of the study highlighted the utility of the proposed approach for grouping clones. Group identification and detection of the climatic impact on yield patterns was evaluated as a measure to increase site-specific productivity.

1. Introduction

Intensively managed plantations supply 33% of the world's non-fuelwood demand, even though their area correspond to only 1.5% of the forests in the world (INDUFOR, 2012). These productive forests have alleviated the historical pressure on native forests in some places (Hayes et al., 2005), and eucalyptus plantations emerge as the pinnacle of fast-growing forests. This genus is well known for the highest growth rate among the hardwoods in the world, where the productivity in Brazil has increased about 3-fold in the past 40 years (Stape et al., 2010). This dramatic increase of eucalyptus productivity is a consequence of the summation of key factors: development of superior clones and silvicultural practices including site preparation, fertilization, weed control and spacing (Stape et al., 2010; Gonçalves et al., 2013).

Intensively managed plantations focus on the manipulation of soil and stand conditions in order to minimize the environmental constraints that may limit tree growth (Fox, 2000). The climate effect, however, cannot be controlled, which highlights the importance to understand its effect on forest production. As noted by several authors,

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for example Almeida et al. (2010) and Scolforo et al. (2016), droughts can dramatically reduce eucalyptus productivity. This climate phenomenon makes plantations more susceptible to attack of pests, disease, and catastrophic mortality (Netherer et al., 2008; Pinkard et al., 2015).

Traditional areas of eucalyptus plantations in Brazil have faced unusual droughts in the past few years (Otto et al., 2015). The market demand for bio products however, has increased and prompted the expansion of eucalyptus plantations even to drier sites (Binkley et al., 2017). These facts have challenged the development and selection of silvicultural regimes and clones to successfully keep commercial plantations with high growth rate in these new conditions.

Changes in silvicultural regimes, such as the reduction in the number of planted trees per hectare (Hakamada et al., 2017), can reduce tree mortality by mitigating the competition for water resources. On the other hand, clonal deployment seems to be more challenging, since the genotype × environment (G × E) interaction, may be substantial, especially in regard to climate variation (Binkley et al., 2017). On one hand, the development of breeding programs has increased eucalyptus productivity and wood quality (Lemos, 2012), but on the other hand, little effort has been extended to verify how the large variety of clones interact with climate (Scolforo et al., 2017). Questions always arise, especially the ones concerning: (1) how does clonal productivity vary across different sites; (2) are there clones with similar volume yield pattern spanning large areas? These questions are crucial in the context of the selection of the most proper clones to match specific sites in order to avoid plantation failure (Gapare et al., 2015).

Some studies have started to address some of these questions, such as Scolforo et al. (2017) and Marcatti et al. (2017). These authors used statistical models for recommending the appropriate places where different clones should be planted. Their methodology focused on the gain of forest productivity by using climate information. Calegario et al. (2005) suggested the combination of climate and/or soil data with mixed effects modeling to improve clonal selection for maximizing forest productivity. Almeida et al. (2010) proposed clonal selection to increase eucalyptus productivity through the use of ecophysiological models.

It is still necessary to acquire better understanding of how clonal productivity varies along a national climate gradient, and if certain clones can be grouped according to similar volume yield patterns. Furthermore, observing how volume yield patterns vary with clonal group and climate is crucial for proposing site-specific management. Clonal grouping may be used by geneticists by searching for a few physiologic characteristics that explain how different clones have similar environmental interaction (Scolforo et al., 2017). This may serve as baseline information for developing superior clones in Brazil.

This paper provides an approach of clonal grouping based on the volume yield pattern of 11 widely planted eucalypt clones, evenly distributed across 17 sites in tropical Brazil. The approach enables assessment of how annual water deficit index variation impacts clonal productivity in tropical Brazil.

2. Material and methods

2.1. Characterization of the sites and database

The database is composed of remeasurement information from 17 research sites that span tropical Brazil (sites: 2, 4, 5, 7, 8, 9, 11, 13, 14, 20, 22, 24, 26, 29, 30, 31 and 33). These sites are part of the TECHS Project (Tolerance of Eucalyptus Clones to Hydric, Thermal and Biotic Stresses), which was launched in 2011 in Brazil and northern Uruguay (Binkley et al., 2017). The database of this study, however, is concentrated in tropical Brazil, which ranges from Paraná to Pará State (Fig. 1).

The TECHS sites are located in the full climate gradient of tropical Brazil (Am, As, Aw, Cfa, Cfb, Cwa, and Cwb) (Alvares et al., 2013). This implies that the studied sites encompass a wide range of mean annual temperatures (18 to 28 °C), annual precipitation (493 to 1674 mm), annual potential evapotranspiration (1333 to 1980 mm) and annual water deficit index (−1202 to −24 mm). The TECHS sites range from dry areas to areas without hot seasons and rainfall limitation.

Soils for these sites are represented by oxisols (68% of the sites), entisols (23% of the sites), and ultisols (9% of the sites), while elevation ranges from close to sea level (36 m) up to 969 m above sea level. Detailed information regarding this project can be found in Binkley et al. (2017), where the authors highlight the unique features of the TECHS project.

To investigate eucalyptus growth, TECHS sites were installed between January and May of 2012. A total of 11 commonly deployed clones (A1, B2, C3, D4, E5, G7, H8, K2, P7, Q8 and R9) were planted at every TECHS site. Every block plot contains 80 trees, equally spaced at 3 x 3 m. All plots were intensively fertilized to mitigate nutrient deficiency and competing weed vegetation was properly controlled (Binkley et al., 2017).

The first plot measurements were conducted between December/2012 and May/2013. After the initial measurement, all TECHS sites were inventoried every six months (last inventories in April/2017). The diameter at 1.30 m aboveground (DBH in cm) and total height (h in m) of all trees were always measured. Individual tree volumes were obtained through the use of the equation developed by Scolforo (2018).

To record weather information, weather stations were installed at all of the TECHS sites. Thus, variables such as annual precipitation (P in mm), average temperature (T_{avg}, ^{0}C), annual potential evapotranspiration (PET, mm) and water deficit index (WDI, mm) were daily recorded. Large climatic variability is apparent (Table 1), and fully expected, given the size of large tropical country such as Brazil. Annual water deficit index is expressed by the difference between the potential water deficit and water storage capacity, where potential water deficit is obtained for months that evapotranspiration excess monthly precipitation (Montes et al., 2015).

$$WDI = -\sum_{n=1}^{12} (PET \geqslant P)(PET - P) + WSC \tag{1}$$

where $(PET \geqslant P)$ is a dummy variable that assumes 0 when $PET < P$ and 1 when $PET \geq P$; n ranges from 1 to 12 corresponding to months; WSC is the water storage capacity in mm; all other variables are defined.

2.2. Standardized volume yields of the clones

While the installation dates varied among the TECHS sites, the stand volume yield (V) was standardized at a common age of 5 years. This age is at the full rotation range of eucalyptus plantations under the clear-cut system for pulpwood production (Fialho and Zinn, 2014).

There are numerous options for growth equations with desirable properties to model biological data (Burkhart and Tomé, 2012), such as the Chapman-Richards and the Logistic model (Raimundo et al., 2017). For purposes of this research, however, the standardization of volume yield was accomplished with a polynomial equation. Typically, polynomial equations are not used for the modeling of biological growth, since they display unstable growth predictions and generally do not contain the logical constraint of V = 0 at Age = 0.

Three patterns of stand volume growth over time can be observed with the plots across the TECHS sites (Fig. 2). The first pattern (1) is based on regular forest growth, where some tree mortality is observed, while the second pattern (2) displays an unusual mortality rate over time. The high mortality rate in the second pattern is probably due to climatic events that induce high mortality and give the impression that growth is not occurring at the stand level. Chapman-Richards or the Logistic growth model can be applied to properly describe the forest development over time under these patterns 1 and 2. These growth models, however, cannot be properly applied to the third pattern. This