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Eucalyptus growth and yield system: Linking individual-tree and stand-level growth models in clonal Eucalypt plantations in Brazil

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ABSTRACT

Linking individual-tree and stand-level growth models is required for estimating future forest stand structure, while maintaining the desired accuracy for forest management decision making. There is a scarcity of studies addressing this issue for clonal Eucalypt stands in Brazil. Thus, this paper aims to develop a compatible individual-tree and stand-level growth and yield system for clonal Eucalypt stands in Brazil. The dataset used in this study is derived from remeasurement information of sixteen TECHS sites. At every site, eleven Eucalypt clones were planted in single block plots, while extra plots under a rainfall exclusion regime were also installed in fourteen sites. Prediction and projection diameter percentile equations were developed, as well as an individual-tree mortality equation and a generalized height-diameter equation. In addition, a detailed explanation of the structural architecture of the developed compatible growth and yield system is provided. Differences when forecasting forest afforestation and updating forest inventories were highlighted in order to provide the proper use of the developed growth and yield system. Finally, the individual-tree equations were validated through the use of the rainfall exclusion regime plots as was the growth and yield system when applied for prediction and projection purposes. The individual-tree level equations provided accurate estimates. The newly developed compatible growth and yield system also displayed unbiased and accurate estimates. The system achieved full compatibility between individual-tree and stand-level estimates and produced accurate stand table estimates. The growth and yield system presented is a powerful analytical tool that can serve to update inventory data in tropical Brazil and also to provide estimates for expected forest afforestation. The system has the capability of providing detailed outputs, which allows forest managers to consider merchandizing the clonal Eucalypt stands into multiple products.

1. Introduction

Growth and yield systems are essential tools for enhancing forest management decision making. For forestry enterprises focusing on the production of a single product, and assuming all merchantable volume is consumed, a stand-level growth and yield system is already capable of providing enough information to maximize forest profitability (Burkhart and Tomé, 2012). This system typically requires the lowest resolution and level of abstraction of growth and yield models. Consequently, the stand-level approach tends to produce accurate estimates of long-term growth (Qin and Cao, 2006). This is a remarkable advantage since forest managers are usually interested in long-term information in order to feed strategic planning (Burkhart and Tomé, 2012).

The limited use of the stand-level approach, however, restricts analyses regarding the capability of merchandizing a forest into multiple products such as pulp, paper, charcoal, or even for higher valued products such as dimensional lumber (Weiskittel et al., 2011). This drawback is related to the fact that the stand-level approach does not contain any information regarding stand structure, and the lack of such

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information constrains the computation of multiple products that a forest might produce (Peng, 2000).

Therefore, to account for stand structure in even-aged stands, a modeling approach with finer resolution should be used. There is a trade-off, however, in the increase of detail of information provided by the growth and yield models (Ferraz Filho et al., 2015) and error propagation. Models that are able to estimate future stand structure are susceptible to higher estimation error, which may compromise the estimation accuracy desired for forest management decision making. Thus, estimates generated from a modeling approach with finer resolution that are consistent with the stand-level estimates seem to be ideal in order to have a better balance between multiple product information and estimation accuracy (Qin and Cao, 2006).

Diameter distribution models are commonly used through parameter recovery methods in order to provide stand table information and in a way that the estimates are consistent to the stand-level estimates (Burkhart and Tomé, 2012). Thus, future estimates of statistical distribution-based, stand tables, with diminished estimation error can be generated. McTague and Bailey (1987) estimated future stand tables for *Pinus taeda* in southern Brazil through the percentile method and the authors achieved full compatibility with the stand-level estimates. Ferraz Filho et al. (2015) applying the method of moments for *Pinus taeda* in Uruguay also reported accurate and consistent stand table and stand-level estimates. The shortcoming of using the parameter recovery methods, however, is that the estimated future diameter distributions are restricted to being unimodal, which can generate biased stand table estimates.

In cases that inventory data are not available, assuming that the future diameter distribution of a given area is unimodal is reasonable. On the other hand, when the goal is to update inventory data, a different approach appears to be required (Pienaar, 1989). Clutter and Allison (1974) started to address this question in a pioneering effort to constructing individual-tree growth models compatible with stand-level estimates. Nepal and Somers (1992) introduced an approach, named generalized stand table projection method, which generates a tree list that is consistent with stand-level estimates. Cao and Baldwin (1999) reported a method, but for *Pinus palustris*, that differs from the Nepal and Somers (1992) method in the computation of tree mortality. Trincado et al. (2003) highlighted a slightly superior performance of the Nepal and Somers (1992) approach compared to the approach of Cao and Baldwin (1999) for *Eucalyptus nitens* plantations in Chile. Meanwhile, Allen et al. (2011) recommended the use of the Cao and Baldwin (1999) approach for *Pinus taeda* stands in USA.

There is a vast literature of methods that produce individual-tree models compatible with stand-level estimates. For clonal Eucalypt stands in Brazil, however, there is a shortage of applications with compatible tree and stand-level estimates. Historically, clonal Eucalypt stands have focused on the production of pulp by assuming that all merchantable stand-volume is consumed, which consequently implies development of single stand-level growth and yield systems, such as the system exemplified in Scolforo (2018). The findings reported by Scolforo et al. (2018), however, demonstrated initiatives with clonal Eucalypt stands aiming to diversify forest production for multiple products. Therefore, there is a need for the development of compatible systems that links individual-tree and stand-level estimates in clonal Eucalypt plantations in Brazil.

The objective of this paper is to develop a new growth and yield system to be applied in clonal Eucalypt stands in Brazil. The approach links individual-tree and stand-level growth models, which results in full compatibility between the estimates. In addition, the newly developed approach allows for: (1) updating the forest inventory for making short-, medium- and long-term projections using the new stand table projection method; (2) predicting forest afforestation yield with the simplification of the stand table method in a statistical distribution-based stand table.

The new and highly detailed growth and yield (G & Y) system is also tested with plots that faced drier climatic conditions, in order to verify its flexibility to predict and project growth under different climate scenarios.

2. Material and methods

2.1. Study area

The TECHS project (Tolerance of Eucalyptus Clones to Hydric, Thermal and Biotic Stresses, www.ipef.br/techs/en) is a unique research platform aiming to investigate Eucalyptus growth across the full Brazilian climatic gradient and northern portion of Uruguay. The project was launched in 2011 with the main purpose to understand and quantify how climate constrains clonal Eucalyptus production (Binkley et al., 2017).

This study used sixteen TECHS sites (Fig. 1): 2, 4, 5, 7, 9, 11, 13, 14, 20, 22, 24, 26, 29, 30, 31 and 33, since our interest was focused on the regions where water availability seems to be the major constraint to Eucalyptus production (Scolforo, 2018). These sixteen sites were installed in soils that vary from oxisols (68% of the sites), entisols (23% of the sites) and ultisols (9% of the sites). Additionally, these sites were installed in areas with elevation close to sea level up to 969 m above sea level.

Finally, it is worth mentioning that there is at least one site installed in each Brazilian climatic zone, which implies that the full climatic gradient of Brazil was covered. Sites are in the Am (tropical and monsoon), As (tropical with dry summer), Aw (tropical with dry winter), Cfa (humid subtropical zone with hot summer and without dry season), Cfb (humid subtropical zone with temperate summer and without dry season), Cwa (humid subtropical zone with hot summer and dry winter) and Cwb (humid subtropical zone with temperate summer and dry winter) climate zones (Alvares et al., 2013).

2.2. Database

The database is composed of remeasurement information of the sixteen TECHS sites. At every site, eleven Eucalypt clones were planted in single block plots (regular plots). At fourteen sites (2, 4, 5, 7, 9, 11, 13, 14, 20, 22, 24, 26, 30 and 31), an extra replicate (plot) was installed for each clone, where these plots were designed to mimic a drier climatic scenario. For the rainfall exclusion regime plots, 30% of annual rainfall was excluded from the system, i.e., never reached the ground. Thus, these plots allowed for the investigation of how each clone grows under climate scenarios that are substantially drier than the current Brazilian climatic pattern. Finally, the eleven clones were categorized in four different clonal groups (Group A: Clone A1; Group B: Clones B2, D4, E5 and H8; Group C: Clones C3, G7, K2, Q8, R9; Group D: Clone P7) for all the modeling analyses, since each clonal group presented the same yield pattern across Brazil (Scolforo, 2018).

Prior to the installation of the plots at each site, weed vegetation and nutrient deficiency were fully eliminated (Binkley et al., 2017). All the installed plots consisted of the same size, 720 m^2, where 80 trees regularly spaced at 3×3 m were planted. Plot measurements started between December/2012 and May/2013 and remeasurements were conducted every 6 months with the last measurement in April/2017.

In the first measurement all the trees were properly labeled at each plot. In the plot remeasurements, these labels were respected in order to maintain the growth record of each individual-tree. This is an important aspect to be mentioned in that these labels allowed for modeling individual-tree mortality with the highest degree of fidelity.

At each plot, all the trees were always measured with respect to their diameter at 1.30 m above ground (DBH in cm) and total height (h in m). Additionally, trees that died from one measurement to the next were identified. Dominant height (H) was defined following the mean top height concept, where H was defined as the average height of the 7 largest trees in DBH at each plot. Finally, basal area ($m^2\,ha^{-1}$) and