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A new model of tropical tree diameter growth rate and its application to identify fast-growing native tree species

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A B S T R A C T

The Atlantic forest biome in Brazil possesses many suitable tree species for cultivation and restoration purposes. This biome was the most rapidly and extensively exploited forest type in Brazil and it displays areas ill-suited for eucalyptus cultivation. Since tropical tree species usually do not form growth rings and long-term growth data are still not available in Brazil, this study addressed a new approach to diameter growth rate estimation. The approach was developed in order to alleviate the shortage of species-specific growth information for the Atlantic forest biome. The two reasons for developing the approach were: (1) the possibility of increased ecological and economic diversification of plantation forests beyond eucalyptus, and (2) the potential to identify suitable tree species for restoration programs in the biome. Either reason requires growth models with sound biological properties. The data used in this study came from 20 native forest fragments and included six tropical tree species. Forest inventory to assess forest growth was first conducted in 2003, while the re-measurement was conducted in 2008. A non-linear exponential model, containing an asymptote parameter as a function of stand density, was fit to estimate tree species diameter growth rate for each of the six tree species in the study. Additionally, based on the exponential model, a formulation of the time required for each tree species to reach a given diameter was developed. The fitted models exhibited high variability among the six tree species, but they performed well with respect to tree growth behavior. Since the model accounted for stand density, it was possible to predict how different stand densities would affect each tree species growth over time. Finally, the tree species *Triplaris gardneriana* Weddell, *Inga vera* Willd. and *Xylopia brasiliensis* Spreng are recommended as potentially fast-growing tree species in the Atlantic forest biome. These tree species exhibited good growth rates regardless the stand density simulated (1600/ha, 2000/ha, and 2400/ha) to reach a dbh of 10 cm (*Xylopia brasiliensis* Spreng - 16 years, 17 years, and 18 years; *Triplaris gardneriana* Weddell - 15 years, 17 years, and 21 years; *Inga vera* Willd. - 25 years, 25.5 years, and 26 years) and showed promising potential for both restoration and production programs. The developed approach reveals a unique diameter growth rate prediction method.

1. Introduction

Brazil possesses a wide diversity of biomes (Amazon, Atlantic Forest, Pampas, Savanna, Semi-arid woodland and Wetlands) resulting in a large diversity of tree species, which contributes to a very significant carbon stock capacity occurring within its borders (totaling 8,514,877 km^2). The State of Minas Gerais occupies approximately 7% of the Brazilian area (586,528 km^2), and it displays landscape variations including Savanna, Atlantic forest, and Semi-arid woodland biomes, with 57%, 41%, and 2% of the vegetation, respectively. These three different biomes harbor a large

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number of tree species, with the total number of tree species estimated at 2401 (Oliveira Filho and Scolforo, 2008).

The Atlantic forest biome in the State of Minas Gerais is composed of seasonal semideciduous and Atlantic rain forests, with the former possessing the majority of the area. The Atlantic forest biome is characterized by great floral diversity occurring at high densities, and it also contains a large number of endemic animals. These characteristics mark this biome as one of the eight most important hotspots for biodiversity conservation in the world (Myers et al., 2000). Scarcity of information regarding tree species growth in this tropical environment, however, raises several challenges for forest management (Clark and Clark, 1999).

One of the major challenges is that the use of many tropical forest tree species for restoration programs often leads to failure because the choice of the species is not based on basic growth and adaptation information for the tree species (Lamb et al., 2005). Weed vegetation often dominates the stand because rapid tree height growth species are usually not selected (Stanturf et al., 2000). Although weed growth is a management problem, the selection of fast-growing tree species could promote early canopy closure in the forest. Thus, after canopy closure, weed vegetation would no longer be detrimental and the planting of shade-tolerant tree species for the purpose of increasing forest diversity could be successful.

The Brazilian Atlantic forest was the most rapidly and extensively exploited forest type during the Brazilian colonial period (Engel and Parrotta, 2001), and many of the exploited areas need to be restored (Rodrigues et al., 2009). The level of degradation in the current Brazilian scenario is closer to 88.3% (Ribeiro et al., 2009).

A second challenge is related to commercial reforestation where the lack of tree species growth information constrains identification of suitable tree species to be planted. The vast majority of planted forests in the State of Minas Gerais are composed of *Eucalyptus* spp. (75%) (IBÁ, 2016). However, the identification of fast-growing native tree species for cultivation offers socioeconomic advantages by increasing the range of possible forest products (Aronson et al., 2007), combined with the adaptability to areas where *Eucalyptus* spp. species are not well-suited. A recent successful example of native tree species cultivation in the State of Minas Gerais is candeia (*Eremanthus erythropappus* (DC.) Macleish), a species that can produce valuable products and develop in rocky soils, which are not suitable for other traditional crops (Silva et al., 2014; Scolforo et al., 2016a).

Condit et al. (1993) suggested that estimation of long-term growth in native forests is possible only by extrapolation of short-term growth records because most tree species do not have growth rings and long-term-data is still not available (Groenendijk et al., 2014). The recent Minas Gerais inventory of its forests in the 2000s (Scolforo et al., 2016b) allows studies towards this direction. The development of forest growth modeling in order to identify tree species with the greatest growth potential in tropical environments has two main advantages for the Atlantic forest biome: (1) help identify additional tree species with good growth rates for restoration programs, and (2) promote increased ecological and economic diversification of plantation forests beyond eucalyptus or other exotic species.

Authors such as Richards (1952), Del Valle (1979), Whitmore (1984), and Ter Steege (1990) proposed methods for estimating growth rates from tree samples in different size classes. They calculated the time required for a tree to grow through the successive size classes if mean diameter growth was maintained. However, these methods encounter limitations arising from small sample size, and the absence of the same species distributed over all size classes. The method developed by Condit et al. (1993) corrects for the lack of size class representation using regression analyses to fit growth rate estimates as a continuous function of diameter at 1.3 m aboveground (dbh). The authors then calculate instantaneous changes in dbh by treating the growth curve as a differential equation. However, the method can result in negative estimates of growth rate for larger trees (Scolforo et al., 2008).

Other methods for estimating forest dynamic changes have recently been proposed by Roitman and Vanclay (2015), who used stationary matrix models to assess the size class dynamics of a forest in central Brazil. Other studies, such as Liu and Ashton (1998), who simulated forest dynamics in Malasya, and Pütz et al. (2011) who evaluated how fragmentation affects forest dynamics in Brazil, are more related to ecological processes. Bec et al. (2015) developed a model to assess tropical tree species growth in India, however, the developed approach incorporates several covariates, which are still unobservable in the Brazilian forestry scenario, since the lack of tree growth records still do not allow for the observation of specific growth patterns in the Brazilian biomes. In spite of their findings, Clark et al. (2015) discussed the issues in the context of design and sampling of tropical environments, highlighting the difficulty in measuring enough variables in the long-term for more accurate studies.

Although several studies developed modeling approaches for tropical environments, there is still a gap in the literature with respect to the development of growth rate estimation methods for individual tree species. Such methods are needed for estimation and prediction of diameter growth rates that identify tree species for potential use in programs of cultivation/production and restoration.

The objective of this study was to develop an approach to estimate dbh growth rate with the purpose of identifying species with high growth potential for cultivation (production of multiple products) and for restoration purposes.

2. Material and methods

2.1. Characterization of the study area

The data used in this study came from the Atlantic forest biome in the São Francisco hydrographic basin of Minas Gerais, Brazil. The São Francisco hydrographic basin is located between latitudes 21° and 7° South and longitude 48° and 36° West and the river's average discharge is 3150 m^3/s. São Francisco is the most important river in the State of Minas Gerais and one of the most important rivers in Brazil due to its length and economic impact on five different states (Scolforo et al., 2008). Meanwhile the Atlantic forest biome in Minas Gerais displays an area of approximately 5,447,085 ha (Scolforo et al., 2015) and possesses landscape variation that ranges from seasonal semideciduous forest to rain forest. Although there is a landscape variation in Minas Gerais, the study area was concentrated in the seasonal semideciduous forest, since its area corresponds to more than 95% of the total Atlantic forest area.

The Köppen climate classification for the study area ranges from Aw (seasonal climate with precipitation greater than 1500 mm, dry winters, and annual average temperature greater than or equal to 18 °C over the majority of the study area) to Cwa (temperate climate with dry winters having temperatures below 18 °C, and hot summers having temperatures above 22 °C) to Cwb (temperate climate with dry winters exhibiting temperatures below 18 °C, and temperate summers having temperatures below 22 °C) in the western region and Cwa to Cwb in southern Minas Gerais (Alvares et al., 2013). Elevations in the region range from 900 to 1500 meters above sea level.

2.2. Field sampling data

The data were obtained from surveys using a multi-stage sampling method in the São Francisco hydrographic basin of the State