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Meteorological seasonality affecting individual tree growth in forest plantations in Brazil

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ABSTRACT

Seasonal meteorological variability within and among years has significant impact on forest productivity, thus understanding its detailed effects on tree growth contributes to the knowledge of the processes controlling forest productivity. This study used high frequency measurements of dendrometer bands (every 2–4 weeks over 1–2 years) to assess tree growth of four different planted forest types (Brazilian native tree species, *Eucalyptus grandis*, *Pinus caribaea* var. *hondurensis*, and *Pinus taeda*) in response to meteorological variables in distinct regions of Brazil. Multivariate linear regression analysis was applied to relate growth as function of meteorological variables. All species responded to multiple meteorological variables related to air temperature and water availability (maximum air temperature ($p < 0.05$), vapor pressure deficit ($p < 0.01$) and actual evapotranspiration ($p < 0.01$)). Dominant trees were more responsive to meteorological seasonality, compared to suppressed trees. Understanding the relations between forest growth and meteorological variables is useful and has practical applications, including the optimization of species zoning, modeling and the evaluation of climate change impacts on planted tree species for restoration or wood production purposes.

1. Introduction

Meteorological variability among and within years has direct and indirect effects on resources availability (light, water and nutrients) to the trees, with significant impacts on forest growth and development (Binkley et al., 2004). Studies performed on natural and planted forest ecosystems have shown that tree growth responds to meteorological variation at different spatial and temporal scales (King et al., 2013; Cristiano et al., 2014; Urrutia-Jalabert et al., 2015). Commercial *Eucalyptus* plantations can significantly increase wood productivity due to increasing rainfall across climatic gradients (Stape et al., 2010). They also show a high temporal resolution response to water supply, growing within the same week after the increase in soil water content (Drew et al., 2008). Pine plantations follow similar patterns of responsiveness to water availability and temperature variations within and among years (Alvarez et al., 2012).

Depending on the climatic region, tree growth is affected by specific meteorological variables. In general, trees growing on dry climates, experiencing limited water availability across periods or seasons, are more affected by the amount and distribution of rainfall and vapor pressure deficit (Callado et al., 2013; Rowland et al., 2014), while trees growing on high latitudes or altitudes and no dry seasons are more affected by variation in air temperature (Spanner et al., 1990; Boisvenue and Running, 2006).

Forest plantations in Brazil, for restoration and wood production, are very productive mainly due to favorable climatic conditions (Stape et al., 2010; Gonçalves et al., 2013; Ferez et al., 2015; Venegas-González et al., 2016), therefore, understand the role of meteorological seasonality on tree growth is essential to maintain current levels of productivity and to predict potential impacts of future climatic scenarios. Meteorological variability within years is especially important to identify specific variables, and how their ranges affect forest growth on specific periods of the year (Rawal et al., 2014; Watt et al., 2014).

Previous studies have successfully assessed the influence of meteorological variables and silvicultural treatments on growth

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rates of planted (Sette et al., 2012; Battie-Laclau et al., 2014) and native tree species (Callado et al., 2004; Cardoso et al., 2012; Grogan and Schulze, 2012), however, studies relating temporally detailed forest growth as a function of meteorological seasonality are still limited for planted forests for both wood production and restoration purposes.

Simulations of climatic scenarios for the next century in South America suggest significant increase in air temperature and changes in distribution and reduction in precipitation (Chou et al., 2014). These changes will certainly affect forest productivity at different scales of space and time. Therefore, a detailed understanding of the interactions between tree growth and meteorological seasonality is important for practical uses, such as species zoning aiming the optimization of wood production on commercial planted tree, modeling production and development of specific species to distinct climatic regions, and to estimate potential impacts of climate change on growth of different tree species (Booth, 2013; Janowiak et al., 2014).

Forest productivity is usually assessed by annual surveys, preventing a detailed evaluation of intra-annual meteorological effects on tree growth. The only method to capture meteorological seasonality affecting individual tree growth is by increasing the frequency of measurements over short periods of time, such as months, weeks or days (Wunder et al., 2013). Thus, this study used dendrometers aiming to precisely evaluate the influence of intra-annual meteorological seasonality on bole cross-sectional area growth of different planted tree species in distinct climatic regions of Brazil. We studied different types of tree plantations (native tree species for restoration purposes, and *Eucalyptus grandis*, *Pinus caribaea* var. *hondurensis*, and *Pinus taeda* for wood production purposes), hypothesizing that regardless the species, individual tree growth variation will match the seasonality of specific meteorological variables, depending on the location in the country.

2. Material and methods

2.1. Experimental sites, tree selection and measurements

The experimental sites were distributed across a wide range of meteorological conditions and soil types in Center-southern Brazil, comprising the states of Minas Gerais (MG), São Paulo (SP) and Paraná (PR) (Fig. 1, Table 1). The tree species presented encompass the two major genus planted in Brazil (*Eucalyptus* and *Pinus*, Gonçalves et al., 2013) and a mix of native tree species most commonly used in forest restoration plantations, with different ages and levels of productivity (Table 2).

2.1.1. Anhembi-SP

The experiment was installed in riparian areas of Tietê River at Anhembi Forest Research Station (AFRS), University of São Paulo (Table 1), located within the Atlantic Forest Biome, dominated by a semi-deciduous seasonal forest (Morellato and Haddad, 2000). In March 2004, 20 native tree species were planted on an abandoned and degraded pasture (Campoe et al., 2010, Table 2). Before planting, the site was dominated by the African signal grass (*Brachiaria decumbens*) which was eliminated by applying 5 L ha^{-1} of glyphosate. Leaf-cutting ants (*Atta* spp. and *Acromyrmex* spp.) were controlled with the systematically placement of sulfluramid-based baits throughout the experimental area.

The experimental design is a complete 2 × 2 × 2 factorial with two levels of each study factor: (i) proportion of pioneer and non-pioneer species: 50:50 and 67:33; (ii) planting spacing: 3 m × 1 m (3333 plants ha^{-1}) and 3 m × 2 m (1667 plants ha^{-1}) and (iii) silvicultural technology: traditional and intensive management (Campoe et al., 2010). For the current study, we selected trees under intensive silviculture at 3 × 2 m planting spacing. This species planting spacing is widely used on restoration plantations on Atlantic Forest Biome (Rodrigues et al., 2009).

The intensive silviculture provided complete control of weeds and alleviated any nutrient limitations to the planted trees. Weed control was carried out chemically by the application of 5 L ha^{-1} of glyphosate across the entire plot, every three months for the first two years, followed by spot applications when necessary. Fertilization was performed annually since planting time, totaling 81 kg ha^{-1} of N, 62 kg ha^{-1} of P, 33 kg ha^{-1} of K, 452 kg ha^{-1} of Ca and 180 kg ha^{-1} of Mg.

Forty pioneers and 17 non-pioneer trees from 10 species were selected across the plots of the selected treatment (described above), with average sizes of cross-sectional area of 153 cm^2, height of 7.5 m, and aboveground biomass of 22 kg for non-pioneer, and cross-sectional area of 303 cm^2, height of 9.1 m, and aboveground biomass of 54 kg to for pioneers. We decided to present growth results separately for pioneers and non-pioneer species to show their differential response to the meteorological seasonality. After the installation of the 57 dendrometers 30 cm above ground level, and 30-day for band adjustments on trees boles, the measurements were performed from 30 to 60 days intervals.

2.1.2. Itatinga-SP

The study was conducted within the Eucflux project (www.ipef.br/eucflux), located in the Southeastern Brazil, in São Paulo State, in a typical commercial *Eucalyptus* plantation belonging to the Duratex company (Campoe et al., 2012, Table 1). The area was planted in December 2002 with *Eucalyptus grandis* (W. Hill ex Maiden) seedlings from a 5th generation seed orchard (Australian provenance of the Coff's Harbour) following minimum cultivation techniques of site preparation (Gonçalves et al., 2014), in a 3.75 m × 1.60 m spacing (1667 trees per hectare, Table 2). Glyphosate was used (4 L ha^{-1}) to eliminate competing vegetation prior to site preparation until canopy closure stage (approximately 18 months after planting). Leaf cutting ants (*Atta* spp. and *Acromyrmex* spp.) were controlled using sulfluramid-based baits whenever necessary.

Fertilization was split according to common practice in commercial forest plantations in Brazil. Fertilizer was applied at planting time, 6 months, 1 and 2 years after planting. The total amount of nutrients applied was 62 kg ha^{-1} of N, 26 kg ha^{-1} of P, 97 kg ha^{-1} of K, 300 kg ha^{-1} of Ca, 144 kg ha^{-1} of Mg, 11 kg ha^{-1} of S, 2.4 kg ha^{-1} of B, 1.6 kg ha^{-1} of Zn and 1.3 kg ha^{-1} of Cu.

Three hundred trees were selected across the 90 ha of the experimental area, comprising 50 suppressed (diameter at breast height, at 1.30 m above ground level, DBH = 10 cm, height = 19.3 m, aboveground biomass = 39.3 kg), 200 average (DBH = 17.5 cm, height = 26.4 m, aboveground biomass = 145.6 kg), and 50 dominant trees (DBH = 22.5 cm, height = 30.3 m, aboveground biomass = 277 kg). Selecting trees from different social status (by size for Itatinga, Nova Ponte and Telêmaco Borba experimental sites) provides the opportunity to show their different ability to respond to meteorological seasonality. After the installation of the 300 dendrometers at DBH position and 30-day buffer for band adjustments on trees boles, the measurements were performed at 14-day intervals.

2.1.3. Nova Ponte-MG

The study was conducted within the project Potential Productivity of Pine in Brazil (www.ipef.br/pppib) located in Southeastern Brazil, Minas Gerais state. The area was planted in January 2008 with *Pinus caribaea* var. *hondurensis* using seedlings from seed orchard located in Agudos-SP, belonging to the Duratex Company. The weed competition was controlled by applying glyphosate