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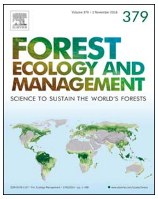

The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay

Dan Binkley[a,b,*], Otávio C. Campoe[c,f], Clayton Alvares[d], Rafaela L. Carneiro[d], Ítalo Cegatta[d], Jose Luiz Stape[e,f]

[a] *School of Forestry, Northern Arizona University, Flagstaff, AZ 86011, USA*
[b] *Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden*
[c] *Federal University of Santa Catarina – UFSC, 89.520-000 Curitibanos, SC, Brazil*
[d] *Instituto de Pesquisas e Estudos Florestais, Via Comendador Pedro Morganti, 3500 - Bairro Monte Alegre, Brazil*
[e] *Department of Forest Sciences, University of São Paulo, 13400 Piracicaba, SP, Brazil*
[f] *Department of Forest Science, São Paulo State University, 18600 Botucatu, SP, Brazil*

ABSTRACT

Intensively managed plantations account for 1.5% of the world's forests, but they meet one-third of the demand for wood products. *Eucalyptus* plantations are among the most productive, with rates of growth depending heavily on genetics, silviculture, and climate. The TECHS Project examines productivity at 36 locations across a 3500 km gradient from Brazil to Uruguay, testing the interacting influences of genetics, temperature and precipitation on stemwood production. Across all sites and genotypes, stemwood production in the middle of the 6-year rotation (the peak period of growth) averaged 22 Mg ha^{-1} yr^{-1}. Production varied by fivefold across sites, and by about 2-fold among genotypes within each site. The best clones at each location grew 1.5–4 Mg ha^{-1} yr^{-1} more than the average for all clones, underscoring the importance of matching genotypes to local site conditions. Contrary to patterns for natural forests across geographic gradients, Eucalyptus production declined with increasing temperature, dropping by 2.5 Mg ha^{-1} yr^{-1} for a 1 °C temperature increase. The temperature effect was likely driven in part by the geographic covariance of temperature and rainfall, as rainfall tended to decline by 78 mm yr^{-1} for each 1 °C increase in temperature. Stemwood production increased an average of 1.5 Mg ha^{-1} yr^{-1} for each 100 mm yr^{-1} increase in precipitation, but when the covariation of temperature and precipitation were included the apparent influence of precipitation declined to 0.4 Mg ha^{-1} yr^{-1} for each 100 mm yr^{-1} increase in precipitation. Future results will determine if within-site reductions in ambient rainfall have the same apparent influences as the rainfall pattern across the geographic gradient, as well as quantifying the importance of insects and pests in affecting growth. The supply of wood from intensively managed plantations will be strongly influenced by both temperature and precipitation at plantation locations, and with changing climates.

1. Introduction

Forests are a dominant vegetation type around most of the world, from frigid regions with very short growing seasons to the hottest tropical areas that have sufficient water supplies to support trees. We depend on forests for the production of fuel and wood products, and global consumption of wood products more than doubled from 1950 to 1990. Total global consumption of wood stabilized in about 1990 at a level of 3.5 billion m^3 yr^{-1}, split about equally for fuel and for industrial products (Sutton, 2014). More than 80% of the world's wood supply was taken from natural forests in 1950, with planted forests supplying less than 20% (Whiteman, 2014). The proportional contribution of wood supplied from natural forests has declined steadily to less than half the global demand in 2015, with actual harvest rates from natural forests declining since 1995. This shift to reliance on planted forests to supply the demands for wood products resulted from increasing area devoted to planted forests (rising by 50% from 1990 to 2015; Payn et al., 2015) combined with accelerating growth rates. Planted forests account for about 7% of all forests (Whiteman, 2014). The most intensively managed, fast-growing plantations account for only 1.5% (54 million ha) of the world's forests, but they supply one-third of the non-fuelwood supply (INDUFOR, 2012). The most

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* Corresponding author at: School of Forestry, Northern Arizona University, Flagstaff, AZ 86011, USA.
E-mail address: Dan.Binkley@alumni.ubc.ca.

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commonly planted species are pines in temperate and subtropical areas (*Pinus*, 42% of planted areas) and eucalypts (*Eucalyptus* 26% of planted areas) in subtropical and tropical areas.

The growth of forests varies across climatic gradients and species (Lieth and Whittaker, 1975, Roy et al., 2001), and plantations of suitable *Eucalyptus* species in the Tropical and Subtropical regions of Brazil are among the most productive forests in the world (Stape et al., 2010, Flores et al., 2016). Intensive research and development into forest growth resulted in a 4-fold increase in wood productivity in Brazil from 1970 to 2015 (Fig. 1). High rates of growth depend on application of results from research programs in genetic improvement (Resende et al., 2012) and silvicultural practices including site preparation, fertilization, spacing and weed control (Gonçalves et al., 2013). Climate strongly influences the growth of planted forests of *Eucalyptus*; a doubling of precipitation from 800 mm yr^{-1} to 1600 mm yr^{-1} along a 100-km gradient in Bahia led to a 3-fold increase in wood growth (from 10 Mg ha^{-1} yr^{-1} to 30 Mg ha^{-1} yr^{-1}; Stape et al., 2004). The addition of supplemental water within sites also increases *Eucalyptus* wood growth, by 20–80% (Stape et al., 2008; Ryan et al., 2010).

Sustaining or increasing the high rates of *Eucalyptus* growth will depend on a variety of changes in the future. Annual variations in precipitation can alter gross primary production and wood production by one-third to one-half (Stape et al., 2008), and any regional changes in climate would likely result in regional changes in production. Statistical and ecophysiological models that incorporate rainfall are commonly used to predict growth (Almeida et al., 2010; Scolforo et al., 2017). Short rotations (commonly about 6–8 years) allow land owners to change land use in responses to changing markets. Increases in the value of agricultural crops could lead to allocation of *Eucalyptus* forests to drier sites, which would require more specific genotypes and new management practices. Most intensively managed *Eucalyptus* plantations use genetically identical clonal trees within each stand to maximize uniformity and growth (Binkley et al., 2002; Stape et al., 2010), and genotypes differ substantially in rates of water use, the efficiency of wood production per unit of water transpired, and in responses to droughts (Hubbard et al., 2010, Blackman et al., 2017). Changes in silviculture could also be important, such as reducing the number of trees planted per hectare to reduce drought-related mortality (Hakamada et al., 2017). Besides these abiotic factors, exotic pests and diseases that harm *Eucalyptus* plantations have been increasingly reported in South America in the last decade with damages levels depending on genotypes and climate (Wingfield et al., 2013). Deployment of *Eucalyptus* clones requires many years of silvicultural evaluation (Resende et al., 2012). A long-standing goal of tree breeders and ecophysiologists is understanding the survival and growth of a large and diverse group of clones (derived from hybrids of various species) across large areas, and how this knowledge can be used to develop manageable ideotypes for tactical and operational decisions (Marcatti et al., 2017; Scolforo et al., 2017).

These impending changes in factors that drive the biological productivity of planted *Eucalyptus* forests led to the creation of an experimental research platform to investigate the influence of climate (water and thermal stresses), spacing and genetics on survival and growth at the level of individual trees and stands. The TECHS Project (Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses, www.ipef.br/techs/en) was launched in 2011 as a collaboration among people from 26 forest companies, 9 universities, and research institutions from Brazil, Uruguay, and the United States. The TECHS Project comprises 36 experimental sites across a 3500-km gradient from the Amazon Region to Uruguay (Tables 1 and 2), examining:

1. How the growth of clonal *Eucalyptus* plantations relate to patterns in climate;
2. How production ecology factors (light and water use, efficiency of resource use, photosynthate allocation) account for the influence of climate;
3. The role of genotypes in determining growth responses to climate;
4. How spacing can mitigate drought effects, survival and growth at the scales of individual trees and plots of trees; and
5. How genotypes can be grouped into ideotypes regarding their ecophysiological responses to hydric and thermal stresses and susceptibility to pests and diseases for operational deployment.

This paper provides a description of the TECHS Project, and basic mid-rotation results for growth patterns and interactions between genetics and environmental conditions. A variety of detailed investigations will come from the Project in the next few years.

2. Experimental design, site descriptions, and core measurements

The core design for TECHS has 18 clones of *Eucalyptus* (Table 3), with 11 clones planted at each of 36 sites for a planned rotation length of 6 years (Figs. 2–4). Only 27 sites are included in this paper, as the others were planted later and had not reached the mid-rotation point

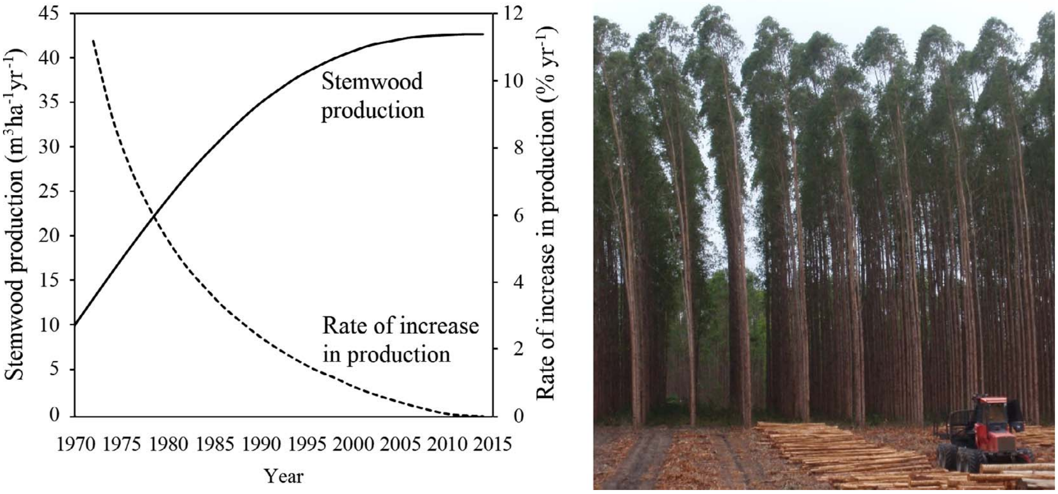

Fig. 1. The productivity per ha of *Eucalyptus* plantations across Brazil increased by 4-fold from 1970 to 2015, as a result of intensification of management and development of fast-growing genotypes. The rate of increase in productivity is currently near 0 (data from IBA, 2015). Image of a typical 7-year-old plantation being harvested with stemwood production across the rotation (mean annual increment) of 25 Mg ha^{-1} yr^{-1} (approximately 50 m^3 ha^{-1} yr^{-1}).