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Influence of spacing regimes on the development of loblolly pine (*Pinus taeda* L.) in Southern Brazil

Denise Jeton Cardoso [a,*], André Eduardo Biscaia Lacerda [a], Maria Augusta Doetzer Rosot [a], Marilice Cordeiro Garrastazú [a], Renato Teixeira Lima [b]

[a] EMBRAPA Forestry, Estrada da Ribeira, km 111. 83.411-000, PO Box 319, Colombo, PR, Brazil
[b] Valor Florestal, Rod. PR-151 s/n, km 207.5. 84.200-000, Jaguariaíva, PR, Brazil

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ABSTRACT

The economic potential of loblolly pine has long been recognized due to the ability to achieve growth levels in commercial plantations that far exceed their expected natural growth. Interest in this species is on the rise as the potential for increased production is becoming more feasible in Brazil and particularly in the US. As production increases and cultural treatments are adopted, understanding long-term outcomes based on similar practices are essential for managers. Long-term spacing studies using a variety of initial densities for different tree species show that initial density has little effect on total wood yield for cycles longer than 20 years. On the other hand, initial density has important implications when considering the intended product and its respective value as well as the overall costs of cultural treatments. This paper reports the 24-year growth of *Pinus taeda* – loblolly pine – in Southern Brazil in response to five cultural regimes. Five initial spacing regimes (2.5 × 1.2, 2.5 × 2.0, 2.5 × 2.8, 2.5 × 3.6 and 2.5 × 4.4 m) combined with cultural procedures generally used in commercial stands were studied. Dendrometric variables analyzed include diameter at breast height (dbh), average and dominant height, site index (SI), basal area, volume per tree and per hectare, and assortment volume; variables were tested using analysis of variance and Tukey test. The results indicate a final lower dbh average in denser spacing regimes but no significant difference in relation to volume per hectare and stand basal area at the end of the 24 year cycle. Our results demonstrate that it is possible to obtain the same volume per hectare, on average 385.7 m^3 ha^{-1}, at the age of harvesting by combining different initial spacings with thinning intensities. The mean annual increment (MAI) was analyzed by reconstructing growth (volume) using the software Pisapro. The simulations showed that MAI has a positive correlation with initial spacing in which the densest spacing obtained a MAI approximately 45% higher than the widest treatment. The results provide managers with long-term data that can be used in forest management planning, e.g. by allowing companies to adjust their operations depending on the costs of planting, maintenance and other cultural treatments. The results also point out that depending on the aim of the production, initial spacing and thinning can be adjusted to meet target product specifications (e.g. larger dbh, lack of knots).

1. Introduction

There are several factors which influence growth in commercial forest plantations. The initial spacing between trees is one of the most basic and essential factors in forest management which in combination with thinning schemes influence the desired final product. Additional information such as species growth and site characteristics are also fundamental in the decision-making process. Although these principles have been applied both in the US and other parts of the world (e.g. Brazil, South Africa), growth rates of southern yellow pine plantations, particularly loblolly and slash pine (*Pinus taeda* and *Pinus elliottii*, respectively), in the US still lag significantly behind the productivity rates in countries like Brazil. Borders and Bailey (2001) assert that the difference in productivity is mainly due to the application of very intensive management practices (e.g. fertilization, mechanical and chemical weed control, among others) that are routinely used outside the US. As productivity increases along with changes in forest practices, information from long-term commercial plantation cycles that use common practices are crucial for management planning. Here we analyze the growth response to different initial spacing regimes in a full-length rotation (24 years) of a loblolly pine experimental stand, followed by commercial plantation prescriptions in

* Corresponding author. Tel.: +55 (41) 3675 5739; fax: +55 (41) 3675 5737.
E-mail addresses: denise.cardoso@embrapa.br (D.J. Cardoso), andre.biscaia@embrapa.br (A.E.B. Lacerda), augusta.rosot@embrapa.br (M.A.D. Rosot), marilice.garrastazu@embrapa.br (M.C. Garrastazú), renato.lima@valorflorestal.com.br (R.T. Lima).

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Southern Brazil. As forestry practices become more homogeneous around the world we expect that our results will make an important contribution to the development of best-practices in commercial plantations.

After the selection of appropriate genetic material, seedling production and soil preparation, the two main variables that can influence the development of trees in a commercial forest are planting density and site characteristics. Site quality determines the potential productivity of a species growing on a particular soil. One of the best predictors of site quality is tree height since it can be expressed as a function of age, thus allowing forest managers to make decisions that consider the site, thinning practices, and their combined effects on production (McEvoy, 2004).

An area's potential for wood production is determined by its site quality but the achieved growth is determined by the amount, quality and distribution of trees in a given site. The amount of tree growing stock is evaluated quantitatively by a number of parameters grouped together as stand density. It describes not only the degree to which a site is being utilized but also the intensity of competition among the trees. At higher densities growth rates of individual trees are slower than at lower densities, even though the total growth per unit area may continue to increase (Davis et al., 1987).

The economic potential of the southern yellow pines for commercial plantations have long been of interest to forest managers mainly in North America. Studies discussing southern yellow pines began as early as the 1930s (e.g. United States Forest Service, 1936) with a renewed interest since the 1970s (e.g. Mann et al., 1971; Sprinz, 1979). More recently, the interest in loblolly and slash pine as commercial forest species in a high productivity context has grown momentum mainly in Southeastern US as large gains in growth have been obtained due to control of competing vegetation, fertilization, genetic improvement, seedling quality and planting method (e.g. Gent et al., 1986; Stearns-Smith et al., 1992; Pienaar and Shiver, 1993; Fox et al., 2007; Antony et al., 2011; Subedi et al., 2012). More optimistic views suggest that growth rates in the US should equal or exceed those obtained in other countries as intensive cultural practices are adopted (Borders and Bailey, 2001).

Although the interest in slash pine as a commercial species in the US is not a novelty, higher levels of productivity have been obtained particularly in countries where the species was introduced. In Brazil, yellow pine species were first tested in 1948 when slash and loblolly pine stood out for their productivity and relatively simple silvicultural treatments (Shimizu, 2008). After years of genetic selection and productivity gains, yellow pine corresponds to approximately 25% of commercial plantations (1.65 million ha) in Brazil; together with *Eucalyptus* plantations, commercial forests in Brazil employ 5% of the country's labor force and are responsible for 19% of the commercial trade surplus (ABRAF, 2012). With the development of the pine industry in Brazil, best provenances were determined and genetic selection was employed to help improve productivity. Furthermore, a number of studies have focused on the relationship between tree density and growth by using different initial planting spacing regimes for *P. taeda* in Southern Brazil (e.g. Leite et al., 2006; Nogueira et al., 2008; Inoue et al., 2011). In the study region, previous research has evaluated the effects of spacing on loblolly pine plantations. However, these studies commonly employ incomplete rotation cycles (8–12 years only) in their analyses which reduces their applicability in understanding the long-term effects of initial density and thinning on growth and productivity (e.g. Gomes et al., 1997; Sanquetta et al., 2003a,b).

Despite the fact that commercial pine plantations in places like Brazil are well-established, the evaluation of factors that affect growth in full-length rotation cycles (~20 years) are still generally lacking in the literature. In order to address this gap we analyzed the effects of spacing on *P. taeda* populations under different thinning schemes over a complete rotation (24 years). We also present information about site quality and discuss best practices for the silviculture and management of *P. taeda* plantations that reflect current regimes used in commercial stands in Brazil.

2. Methods

2.1. Study site

The plots assessed in this study are located in the *Lajeado Farm*, municipality of Jaguariaíva, Northeast of Paraná State, Brazil (UTM 22S 630700E and 7307713N). The region has a history of using loblolly pine in commercial plantations since the 1960s. In this region, and in many other parts of Southern Brazil, the forest sector is a significant contributor to local and regional economies: Paraná State has an area of approximately 605,000 ha dedicated to commercial pine, which corresponds to approximately 37% of the total area of pine plantations in Brazil (ABRAF, 2012). The study site is a Humic Regosol soil and the climate is subtropical (Cfb under Köppen classification) with an average temperature for the warmest month of the year below 22 °C. The area analyzed is a second rotation pine forest; silvicultural treatments used include prescribed burning for weed control at year 1 in 1987 (a method which has since been replaced by herbicides) and no fertilization was used.

2.2. Treatments and variables

The experiment was established in 1987 and was set up as a complete randomized block design in which we monitored the growth of *P. taeda* over 24.4 years. Trees were measured at ages 3.5, 4.5, 5.9, 6.9, 7.7, 8.8, 12, 19.3 and 24.4 years. While other studies from the study site have discussed initial results up to year 12 (Sanquetta et al., 2003a,b; Gomes et al., 1997) we have focused on the results from the complete rotation which includes detailed analyses of the period between years 12 and 24.

Five different spacing regimes (2.5×1.2, 2.5×2.0, 2.5×2.8, 2.5×3.6 and 2.5×4.4 m; spacing between rows was maintained at 2.5 m) were randomly arranged in six continuous blocks of 0.43 ha (Table 1) in a 2.97 ha stand. Each treatment was designed to have two rows of trees on every side (edges) aiming at avoiding interference from neighboring plots. No soil analysis was performed; however, the position in which the blocks were placed – transversal to the terrain slope – suggests that some variation in the site quality was expected. Such variation was later confirmed (Gomes et al., 1997) but it did not hinder the analysis of the treatments.

Two thinning events took place at the site: the first at year 12, using a combined systematic every sixth line and selective (smallest trees) thinning, and the second at year 17, following a selective thinning procedure. This information may be relevant to some simulation and modeling procedures. No data collection occurred immediately after each thinning nor prior to the thinning at year 17.

Lack of measurements before and after thinning can lead to considerable bias in predicting estimates of basal area and dominant height (Snowdon and Woollons, 1993). Consequently, thinnings were simulated using the Pisapro software (Scolforo, 1997), using the thinning regimes described above as input. As a modeling software for growth and yield, Pisapro requires the following input data: site index, basal area, dbh and height. For the simulations we used data from populations at year 12 and thinning intensities were modeled to achieve a final density of around 400 tree ha^{-1} (Table 2), which requires different intensities depending on the