



Influence of spacing regimes on the development of loblolly pine (*Pinus taeda* L.) in Southern 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 $385.7 \text{ m}^3 \text{ ha}^{-1}$, 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).

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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

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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, thinning simulations 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

Table 1

Spacing regime characteristics in terms of tree distribution, area and number of trees measured.

Spacing (m)	Spacing scheme available space per tree (m ²)	Number of trees (ha)	Plot area (m ²)	Number of trees per plot
2.5 × 1.2	3	3333	234	78
2.5 × 2.0	5	2000	210	42
2.5 × 2.8	7	1428	315	45
2.5 × 3.6	9	1111	378	42
2.5 × 4.4	11	909	440	40
Total			1577	247

Table 2

Number of trees during a 24-year loblolly pine plantation cycle: initial, pre-thinning (year 12), after first thinning (year 12), and after second thinning (year 17; final spacing). Note that a natural mortality of 9%, 3.5%, 2.6%, 1.7% and 0% (from the sparsest to the densest spacing respectively) took place between initial spacing density and the density recorded at pre-thinning in year 12.

Spacing (m)	Number of trees ha ⁻¹			
	Initial	At age 12	After 1st thinning	After 2nd thinning
2.5 × 1.2	3333	3034	1484	627
2.5 × 2.0	2000	1929	959	571
2.5 × 2.8	1428	1391	835	492
2.5 × 3.6	1111	1092	601	441
2.5 × 4.4	909	909	500	383

initial spacing (i.e. areas of greater tree density were subjected to more intense thinning events), aiming at reaching final volumes consistent with the results observed in the field.

The modeling of the thinning regimes was designed to have a residual stock of at least 400 trees per hectare as such a density is widely used in commercial stands in Brazil. Thus, considering the varying initial densities in relation to final densities, the two thinning schemes eliminated 79% of the trees in the densest treatment (2.5 × 1.2 m) and around 58% of the trees in the widest treatment (2.5 × 4.4 m). At the first thinning, the number of trees reduced from 40% in the 2.5 × 2.8 m treatment to 51% in the 2.5 × 1.2 m treatment. Thinning intensity, especially in the two densest spacings, was constrained by the risk of wind damage to tree crowns that can occur if thinning is too severe. Therefore, this study aimed at assessing the responses of dependent variables to each treatment considering the thinning schemes used.

The volume per tree and per assortment was calculated using a fifth degree polynomial procedure (Assis et al., 2001) and the equation adjustment was achieved by using a group of trees in a nearby area following the Hohenadl method for volume calculation. The equation used is:

$$d_i = dbh \times [\beta_0 + \beta_1 \times (h_i/H) + \beta_2 \times (h_i/H)^2 + \beta_3 \times (h_i/H)^3 + \beta_4 \times (h_i/H)^4 + \beta_5 \times (h_i/H)^5]$$

where β_i = Estimated coefficients; d_i = Corresponding diameter to specified height h_i (cm); dbh = diameter at 1.3 m of height (cm); H = total height (m); h_i = commercial height (m).

The site index, using year 20 as the base age, was obtained from the dominant height calculated for each block and for each spacing regime. Dominant height was considered as the average height of the largest 100 trees per hectare. Such a procedure is common practice as thinning does not influence the canopies of dominant trees and they are therefore the most stable height-based indicators of site productivity (Skovsgaard and Vanclay, 2008). To calculate the site index, we used an adjusted site equation for *P. taeda* in the study region (Scolforo et al., 2001); site index was used to evaluate the effect of site across spacing regimes and between blocks

by using ANOVA and pairwise comparison (Tukey test). Site index was calculated by:

$$S.I. = \exp(5.75103856) \times [h_{dom} / \exp(5.75103856)]^{(I/I_{ref})^{0.23068992}}$$

where h_{dom} = dominant height (dbh height of the 100 largest trees per hectare at the time of the measurement); I = age in years; I_{ref} = reference age (adjusted for 20 years); S.I. = site index (dominant height at the reference age).

3. Results

3.1. Height and site index

The initial spacing did not significantly influence the average height and dominant tree height at the end of the 24 year rotation. The average height varied between 21.8 and 22.6 m and the dominant tree height varied between 23.2 and 23.9 m (Table 3). On the other hand, the analysis of variance found that there are significant differences between blocks for both average height ($p < 0.01$) and dominant tree height ($p < 0.05$) which suggests that environmental factors may have an impact on these variables.

The site index calculated at the end of rotation did not show significant differences between initial spacings (Table 4). In contrast to the spacing regimes, significant differences between blocks were observed: block 1 is less productive and is statistically different from the more productive blocks 5 and 6 (Table 4). This confirms that the strategy of using a randomized block design substantially reduced the error term compared to that which would have been obtained if a fully randomized design had been used. The difference among blocks for site index was similar to that reported by Gomes et al. (1997) for the same area.

3.2. Dbh and tree volume outside-bark

The analysis of dbh and tree volume outside-bark over the 24 year cycle showed that the initial spacing influenced

Table 3

Average height and dominant height of the final three measurements (year 12, 19.3, and 24.4) for each initial density.

Variable	Initial number of trees (ha ⁻¹)	Age (years)		
		12	19.3	24.4
Average Height (m)	3333	13.8	19.7	21.8 ^{ns}
	2000	14.3	20.5	22.6 ^{ns}
	1428	14.2	20.0	22.2 ^{ns}
	1111	14.6	20.1	22.3 ^{ns}
	900	14.4	20.0	21.8 ^{ns}
Dominant Height (m)	3333	15.2	20.7	23.2 ^{ns}
	2000	16.2	21.4	23.4 ^{ns}
	1428	15.5	21.1	23.9 ^{ns}
	1111	15.7	21.1	23.4 ^{ns}
	900	15.5	20.8	23.2 ^{ns}

p values for treatments (spacing) at age 24.4. $p_{average}$ height value: 0.6423; $p_{dominant}$ height value: 0.9023; ns: not significant.

Table 4
Site index for each treatment at different ages and site index for each block and their grouping following a pairwise comparison (Tukey test).

Treatments (initial spacing)	Site index			Blocks	Site index
	12 years	19.3 years	24.4 years		
3333	21.3	21.2	20.5 ^{ns}	1	18.8 a
2000	22.5	21.9	20.7 ^{ns}	2	20.4 ab
1428	21.7	21.6	21.2 ^{ns}	3	20.6 ab
1111	21.9	21.5	20.7 ^{ns}	4	21.3 ab
900	21.7	21.2	20.6 ^{ns}	5	21.7 b
				6	21.5 b

p values at age 24.4; *p*_{site index} value 0.9015 for spacing; *p*_{site index} value 0.0142 for blocks. Pairwise comparisons (Tukey test): blocks with the same letters (a and b) have means that are statistically similar. Site index calculated considering year 20 as base age.

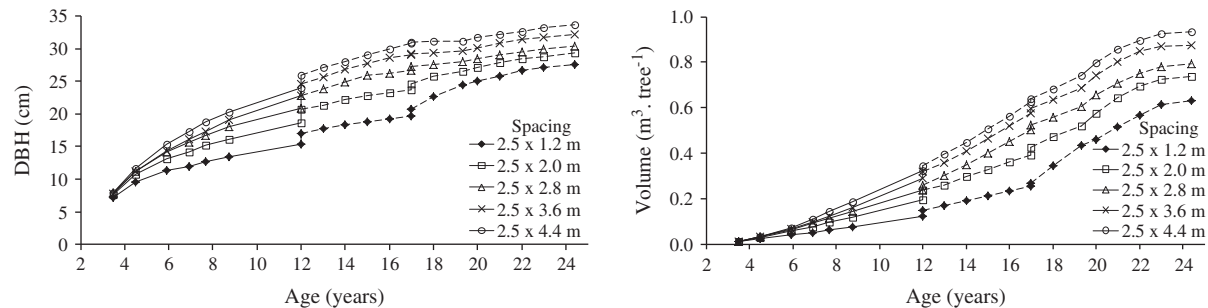


Fig. 1. Changes in dbh (left) and tree volume outside-bark (right) for each initial spacing. As no measurements were taken after first and second thinning (year 12 and 17, respectively) a complete growth tendency curve was depicted using simulations of Pisapro.

Table 5
Means of dbh (cm) and volume outside-bark (m³) with pairwise comparison at different ages in relation to initial density and at the end of the 24 year rotation.

Variable	Initial number of trees (ha ⁻¹)	Age (years)			<i>P</i> value
		12	19.3	24.4	
Dbh	3333	15.3	24.5	27.5 a	1.32E–07
	2000	18.7	26.5	29.4 ab	
	1428	20.9	28.0	30.4 b	
	1111	22.8	29.6	32.2 cd	
	900	24.0	31.2	33.6 d	
Volume outside-bark	3333	0.1238	0.4332	0.6326 a	3.84E–07
	2000	0.1942	0.5211	0.7395 ab	
	1428	0.2394	0.5744	0.7920 b	
	1111	0.2904	0.6447	0.8754 cd	
	900	0.3230	0.7405	0.9355 d	

p values for treatments (spacing): *p*_{dbh} < 0.01; *p*_{volume outside-bark} < 0.01. Pairwise comparisons (Tukey test): treatments with the same letters (a, b, c, d) have means that are statistically similar at age 24.4.

significantly the development of trees throughout the rotation (Fig. 1 and Table 5). As a general trend, the influence of initial spacing on dbh was already visible by the third year while the influence on volume per tree was distinguishable by year 6. The densest initial spacing showed consistently lower growth rates in relation to dbh and volume per tree in comparison to the other spacing regimes. The difference between the densest and widest spacing was 6.6 cm (18%) for dbh and 0.3029 m³ (32%) for volume outside-bark at the end of the rotation (Table 5). The two thinning episodes (years 12 and 17) positively influenced volume per tree and dbh; however an individualized analysis of their effects cannot be established as no measurements took place after each thinning event (only at year 19). In this case we simulated the effects of thinning using Pisapro (see below).

At the time of the final measurement the results also indicated a statistical similarity for both variables (dbh and volume) between the two densest spacings (3333 and 2000 trees ha⁻¹) and between

the two widest spacings (1111 and 900 trees ha⁻¹). The intermediate spacing (1428 trees ha⁻¹) is statistically similar to both the 2000 and 1111 trees ha⁻¹ spacings (Table 5).

The differences among treatments in relation to dbh distribution can be further observed by the distribution of trees per diameter class. The dbh frequency distribution curves show differences across spacing densities with a higher concentration of trees with larger dbh occurring in less dense spacings. In the two densest spacings (3333 and 2000 trees ha⁻¹) the majority of trees are smaller than 30 cm dbh (54% and 57% respectively), while for the other spacings (1428, 1111 and 900 trees ha⁻¹) most trees (54%, 65% and 78%, respectively) are distributed in the diameter classes higher than 35 cm. Moreover, in the widest spacing approximately 42% of trees occur in the diameter classes higher than 40 cm dbh. Additionally, there is a noticeable skewing in the dbh frequency curve towards lower classes for the densest spacing while for the widest spacing it is skewed towards the higher diameter classes (Fig. 2).

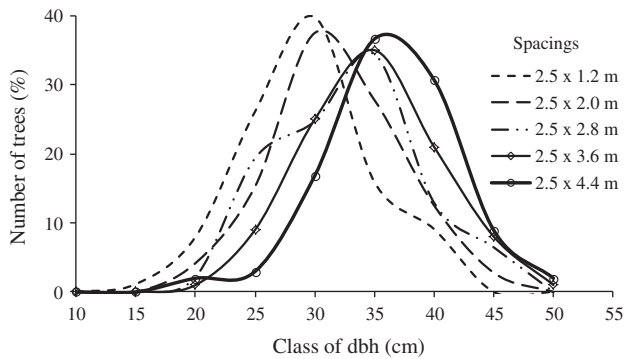


Fig. 2. Percentage of trees by dbh class for each initial spacing regime at year 24.4.

3.3. Basal area and volume outside-bark per hectare

The analyses of the effects of initial spacing on basal area and volume outside-bark per hectare indicated no significant differences among the five treatments at the end of the 24 year rotation (Table 6).

Both basal area and volume outside-bark per hectare showed a steady increase until the first thinning was performed (year 12; Fig. 3) at which point differences between spacing/thinning regimes reached a point of no visible difference by year 19. After year 19 some difference (although not statistically significant) was observed between initial spacing regimes for both variables. Although some variation was observed throughout the rotation among the initial spacings in relation to basal area and volume per hectare, the statistical analysis showed no significant impact of the treatments on the variables analyzed at age 24.4 ($p > 0.5$;

Table 6). It is likely that the greater number of remaining trees in denser spacings compensated for their lower levels of dbh growth in the first half of the cycle (Fig. 3; see also discussion).

3.4. Assortment volume and mean annual increment (MAI)

In assessing the assortment volume, none of the spacing regimes generated yields corresponding to 10% of the total volume per hectare considering a minimum small end diameter (SED) of at least 35 cm (Table 7). On the other hand, for a SED between 25 and 35 cm the widest spacing yields accounted for 55% of the total volume and the densest spacing, for 27%; for SEDs between 18 and 25 cm, these results were inverted, with 27% of total volume being produced in the widest spacing and 48% in the densest. Finally, considering a SED between 8 and 18 cm, the percentage of volume varied from 12% for the widest spacing to 24% for the densest. The results showed that more than 50% of the volume generated by the widest spacing regimes (900 and 1111 trees ha^{-1}) corresponded to SEDs greater than 25 cm while more than 50% of the yield of the densest spacings (3333 and 2000 trees ha^{-1}) corresponded to SEDs of less than 25 cm. The results for the intermediary spacing (1428 trees ha^{-1}) showed a middling value between those obtained for the widest and densest spacings, being slightly skewed towards a SED greater than 25 cm.

The results also showed that the densest spacings produced less volume in a higher SED even though they were subjected to a more intense thinning. It is important to note that the goal of applying thinning regimes was to reduce tree density to a similar final number of trees between treatments which requires thinnings of different intensities. Although the final number of trees was not identical between treatments, we found no statistically significant difference between the densities ($p > 0.05$).

Table 6

Means of basal area ($\text{m}^2 \text{ha}^{-1}$) and volume outside-bark per hectare ($\text{m}^3 \text{ha}^{-1}$) at different ages for each initial density.

Variable	Initial number of trees (ha^{-1})	Age (years)		
		12	19.3	24.4
Basal area	3333	58.7	28.3	37.0
	2000	55.3	31.1	39.9
	1428	48.9	30.6	36.9
	1111	45.3	30.9	37.1
	900	42.1	30.6	34.7
Volume outside-bark per hectare	3333	375.6	255.4	374.7
	2000	374.7	295.7	423.0
	1428	332.9	281.5	387.2
	1111	317.1	284.4	387.4
	900	293.6	279.7	356.1

p values for treatments (spacing) at age 24.4; $p_{\text{basal area}}$ value: 0.9076; $p_{\text{volume outside-bark}}$ value: 0.7847.

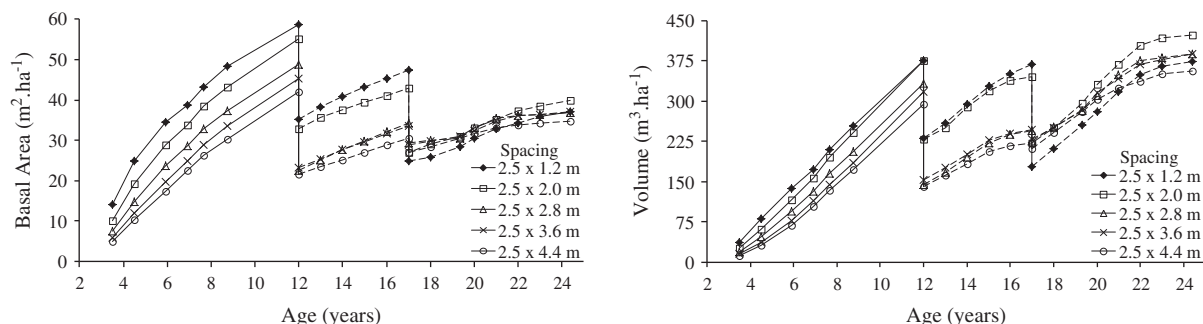


Fig. 3. Development of the basal area (left) and volume outside-bark per hectare (right) for each initial spacing. As no measurements were taken after first and second thinning (year 12 and 17, respectively) a complete growth tendency curve was depicted using simulations of Pisapro.

Table 7
Means of assortment volume outside-bark for different SEDs, commercial volume (outside-bark), tree stump and tip volume, and total volume at year 24 for each initial spacing regime.

Number of trees ha ⁻¹		Volume (m ³ ha ⁻¹)						
Initial	Final	SED (cm)				Commercial	Tree stump/tip	Total
		>35	25–35	18–25	8–18			
3333	627	0 (0%)	99 (27%)	174 (48%)	87 (24%)	361	14	375
2000	571	3 (1%)	160 (39%)	172 (42%)	73 (18%)	409	14	423
1428	492	12 (3%)	168 (45%)	136 (36%)	57 (15%)	375	12	387
1111	441	19 (5%)	188 (50%)	119 (32%)	49 (13%)	376	11	387
900	383	20 (6%)	191 (55%)	94 (27%)	40 (12%)	346	10	356

SED: small end diameter; percentages were calculated in relation to commercial volume.

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 45.4% higher than the widest treatment. However, the differences between spacing regimes varied widely: the densest spacing regimes of 3333 and 2000 trees ha⁻¹ differed by only 2.2% and the difference between the regimes of 1428 and 1111 trees ha⁻¹ was also minimal (4.2%). In contrast, the difference between initial spacing regimes of 2000 and 1428 trees ha⁻¹ was around 24.2% and the difference between the two widest spacings was 10% (Table 8). Note that to a large extent this effect can be attributed to the greater volume harvested from the two densest spacings at the first and second thinning, because in these treatments much more trees were cut.

The simulation of growth showed that the influence of thinning on volume varied across initial spacing regimes. While the yield of the two densest spacings reached pre-thinning volume levels after the first thinning, the volume generated by the three widest spacings recovered only partially from the first thinning and at the time of the second thinning were 40% lower than pre-thinning levels at year 12. In relation to the effects of the second thinning on volume, the results showed that all spacing regimes recovered to their pre-thinning levels by the end of simulation. We also noted a significant reduction in volume after the second thinning for the densest spacing.

The results demonstrate that thinning can hide or suppress the differences between basal area and volume per hectare in various spacing regimes, as reported by Snowdon and Woollons (1993).

4. Discussion

4.1. Height and site index

The initial spacing did not significantly influence the average height and dominant tree height at the end of the rotation, which is consistent with the pattern reported for the study area at year 12 (Sanquetta et al., 2003b) and elsewhere (e.g. Clark et al., 2008). Our results are consistent with the general pattern that it is the diameter, not the height, which is affected by initial spacing and thinning regimes (discussed further below).

It is possible that the range of spacings tested was not sufficient to produce significant differences in height. McEvoy (2004) suggests that in crowded stands a higher proportion of wood is devoted to elongating the top of the tree, probably to improve its chances of positioning leaves in sunlight. When stands are not crowded, trees will concentrate proportionally more wood in lower parts of the stem, possibly as a way of improving the transportation of water and nutrients to the leaves, or to add extra strength to the stem, thus making it more wind firm.

In relation to the site index, our results suggest that the study area is a low (poor) to medium productivity site. McEvoy (2004) notes that on a good site one can expect to find trees 30% taller than trees of the same age on a poor site. This variation is consistent with the results from our study site that show maximum values of 20.5–21.2 m at year 20, which are notably lower than the maximum values found in the region, 26 m.

The site index results are consistent with the values obtained for MAI (20–29 m³ ha⁻¹) which indicates an area of low to medium

Table 8
Assortment volume harvested and simulated mean annual increment (MAI) in volume.

Initial number of trees (ha ⁻¹)	Treatment (thinning)	Harvested trees (ha ⁻¹)	Volume (m ³ ha ⁻¹)						Total	MAI
			SED (cm)				Commercial	Tree stump/tip		
			>35	25–35	18–25	8–18				
3333	1st	1484	–	–	–	115	115	20	135	–
	2nd	923	–	–	42	140	182	7	189	–
	Clearcut	627	–	99	174	87	360	14	374	28.6
2000	1st	959	–	–	–	129	129	7	136	–
	2nd	399	–	–	65	57	122	3	125	–
	Clearcut	571	3	160	172	73	408	14	422	28.0
1428	1st	835	–	–	29	111	140	3	143	–
	2nd	65	–	–	9	10	19	0.5	20	–
	Clearcut	492	12	169	136	58	375	12	387	22.5
1111	1st	601	–	–	55	64	119	5	124	–
	2nd	50	–	–	11	6	17	0.5	18	–
	Clearcut	441	19	188	119	49	375	11	386	21.6
900	1st	500	–	–	42	68	110	4	114	–
	2nd	26	–	–	–	7	7	3	10	–
	Clearcut	383	20	191	95	40	346	10	356	19.7

SED: Small end diameter. Age of clearcut: 24.4 years.

productivity compared to the productivity found in the surrounding region ($18\text{--}40\text{ m}^3\text{ ha}^{-1}$ at age 20; Kronka et al., 2005). The productivity of the study area is within the range of the results obtained for sites in the US (~ 18 to $29\text{ m}^3\text{ ha}^{-1}$ mostly for rotations of around 8 years; Burns and Hu, 1983; Evans, 1992).

Although no soil analyses were performed locally to investigate the relationship between growth performance and soil properties, such associations have been reported for loblolly pine and the soils in the study region are considered to be poor. Bognola et al. (2010) reported that sites with soils of higher clay content result in loblolly trees with a greater annual mean increment; additionally the authors discussed the existence of positive correlations among tree wood volume, soil macroporosity and aeration porosity. Restrictions in growth might also be correlated to the fact that fertilization was not employed at the study site. Dedecek et al. (2008) showed that the soil at productive sites present higher P and K contents, higher pH and base saturation, and lower Al saturation percentages. In relation to the effects of fertilization on growth, Will et al. (2006) described an increase in height from 14.8 m to 19.3 m, an increase in dbh from 14.5 cm to 19.3 cm, and an increase in basal area from 31.9 to $38.3\text{ m}^2\text{ ha}^{-1}$, at age 13; in this experiment the authors mentioned yearly application of N both in wet and dry sites (Bonifay series and Rigdon/Pelham soils, respectively). Other authors have also explored the positive effects of fertilization on loblolly pine growth (e.g. Fox et al., 2007; Jokela et al., 2010).

We expect that the use of fertilization should increase production in order to counter-balance soil deficiency in terms of K and Zn, especially in the densest spacing regimes that may require greater amounts of nutrients. Low levels of such nutrients in the soil have been described as having a correlation with low growth levels in our study region (Martins, 2011). Jokela et al. (2010) in a study on poorly drained soils (Ultic Alaquods – Pomona fine sands) and with nutrient reserves inherently low, reported an increase in the percentage of chip-n-saw (C/S) and sawtimber from 39% in the loblolly pine control treatment to 74–87% in the fertilizer and/or weed control treatments at year 25. Furthermore, a recent study in Brazil using clones of *P. taeda* developed in the US showed that after 18 months the application of fertilizers resulted in trees more than 20% higher as compared to plots without fertilization in sites considered to be naturally fertile. To our knowledge this is the first experiment that assesses the effects of fertilization on clones used both in the US and Brazil (IPEF, 2012). In this context we believe that the use of fertilization not only in poor to medium productivity sites, typical of the conditions found in most pine plantations in Southern Brazil, but also in more fertile sites, would likely have a significantly positive impact on productivity and should be considered in addition to expected yield, environmental, and economic factors.

4.2. Dbh and tree volume

The growth in diameter was greatly influenced by competition between trees beginning at year 6. Therefore, the first thinning at year 12 can be considered late and did not generate the expected dbh growth recovery of the remaining trees, possibly due to environmental factors such as inadequate moisture and light. Note that no measurements were performed before and after thinning, so we do not have annual growth records. Our discussion is based on the measurements of the remaining trees taken 7 years after the first thinning (year 12–19). In our study area, a significant reduction in precipitation (up to 50% reduction) occurred in the region around the time of the first thinning (1999; Fig. 4). The negative correlation between dbh growth and moisture availability is consistent with Friend and Hafley's (1989) study that evaluated several environmental variables and found that both cumulative

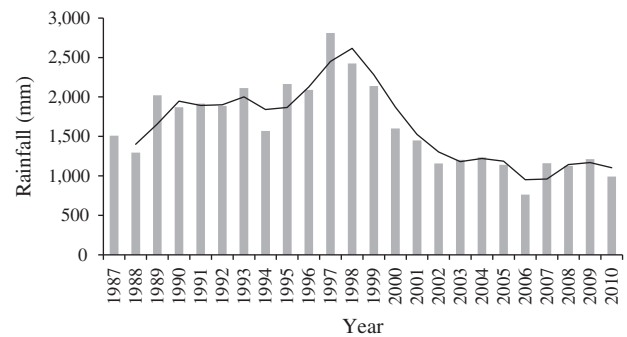


Fig. 4. Rainfall per year in the study region (from ANA, 2013).

mean monthly air temperature from March to May and increased soil water content in September had a positive impact on the radial growth of loblolly pine in central North Carolina. Although the reduction in growth (dbh) was observed for all treatments in our study, the denser treatments seem to have been more severely affected than wider regimes. This is also consistent with the results of Stogsdili et al. (1992) who found significant correlations between thinning and density on the capacity to manage water availability in loblolly pine stands. Although our analysis did not include an assessment of the correlation between precipitation and growth (or any other environmental variables), our results suggest that a link between these variables exists which is consistent with findings elsewhere and should be further studied.

Although our analysis did not include an assessment of the correlation between precipitation and growth (or any other environmental variables), our results suggest that a link between these variables exists which is consistent with findings elsewhere. Michélot et al. (2012) identified sensitivity to precipitation from May to July for dominant tree growth of *Fagus sylvatica*, *Quercus petraea* and *Pinus sylvestris*; the authors also note differences in the species' vulnerability to climate and soil water deficits, in a temperate forest. Plauborg (2004) reported that for *Picea abies*, water supply significantly influences radial-growth responses; for *P. sylvestris* and *Acer pseudoplatanus* the growth responses to climate and soil water deficits are very limited when stand density is reduced.

The difference of 6 cm between the average dbh of the widest and the densest spacings in this study confirms a trend also observed by Bowling (1986) for slash pine on a 20-year-old stand thinned at age 15. The author found an average difference of 4.8 cm in dbh between trees planted at initial spacings of 2500 and 1000 trees ha^{-1} (dbh 17.8 and 22.6 cm, respectively).

Volume per tree followed the same trend for the respective planting densities, indicating a 50% difference in volume between the densest and widest spacing regimes. Considering that growth in diameter was greatly influenced by spacing and volume is positively correlated to dbh, a positive correlation between initial spacing and volume per tree is expected. Therefore, the spacing regimes that allow for greater development of tree diameter would result in a higher volume per tree.

Plantations with wider spacing regimes allow for better development of the tree canopy, thus leading to an improved growth in stem diameter. More wood is produced by trees with large crowns than by those with small ones but branches on the lower stem reduce the quality of lumber by causing the formation of knots (Kozłowski and Pallardy, 1997). Therefore, a good practice to reconcile spacing and productivity would be selecting crown ideotypes that are well suited to each initial spacing regime. Dickmann (1985) reported that densely spaced, short rotation, intensively cultured plantations call for narrow-crowned trees, whereas a broad crowned tree may be better suited for widely spaced regimes used for growing sawlogs.

In order to optimize the yield capacity of a stand the trees should have enough space to maintain a healthy canopy which is especially important in periods of higher growth (younger stages). In relation to the tradeoffs between growth and density [Dean and Baldwin \(1996\)](#) state:

In order to maintain acceptable average growth rates, density must be maintained at levels that promote deep canopies and large, mean-live-crown ratios. According to these results, if the canopy possesses these properties at the stage when growth becomes independent of stand density, the high growth rates associated with these properties will be maintained. However, if stands are allowed to become too dense, canopies will have shallow depths and small live-crown ratios when growth becomes independent of density and will exhibit slow growth despite the crown being independent of density.

4.3. Basal area and volume per hectare

Basal area, as a measure of density of a stand, can be transformed into the relative density index when divided by the square root of d_g (quadratic mean diameter). This index allows for further analysis of the growth conditions of a study area. [Davis et al. \(1987\)](#) note that the ability of trees to respond to thinning is significantly reduced when values for the relative density index are higher than 60. Considering that our results produced values between 59.9 and 73.6, new thinning events would likely not result in higher levels of production and a clear-cut might be prescribed.

Although there were no statistically significant differences between the volume produced at the end of the rotation across the spacing regimes, the densest spacings (3333 and 2000 trees ha^{-1}) are likely to be the most suitable for the study region as there is an optimized use of the production capacity of the site (MAI between 29.1 and 28.5 $\text{m}^3 \text{ha}^{-1}$, respectively). Taking into consideration the limited difference in terms of productivity between the densest spacings (2%) and overall implementation and maintenance costs, an initial density of approximately 2000 trees ha^{-1} is more likely to be the best cost-benefit choice for poor to moderate quality sites similar to the study region.

4.4. Assortment volume

The results of assortment volume at year 24 clearly reflect the growth conditions for each spacing regime: between 55% and 60% of the wood volume is of higher commercial value ($\text{SED} > 25 \text{ cm}$) in the widest spacings while in the densest spacings the percentage drops to between 27% and 48%. In lumber and wood veneer production, common forest management practice aims at obtaining at least 50% of the commercial volume made up of logs with a small end diameter greater than 25 cm by the end of the rotation. In the study region, [Cardoso \(2009\)](#) described the management of commercial forests for lumber in which 57% (reaching up to 70%) of the volume was composed of logs with a small end diameter larger than 23 cm (initial spacing 1600 trees ha^{-1} and two thinning events in a 19-year rotation).

5. Conclusion

The decision to perform one or two thinnings will depend on the end use of the wood; however, a brief economic analysis suggests that probably the best thinning regime for a site with poor to medium productivity would include one thinning and an anticipated clearcut at year 18, or, alternatively, no thinning (for pulpwood production) and clearcut at year 15. Considering thinning at ages 12 and 17 and clearcut at age 24, the Internal Rate of Return

(IRR) lies close to 8% for all treatments, except for the densest one (IRR = 6.4%). Simulating earlier thinnings at ages 9 and 13, and clearcut at age 18, to the same volume yield, the IRR was around 11% for all treatments, except for the densest one (IRR = 8.9%). Therefore decisions on the number and intensity of thinnings should take into consideration the varying economic factors related to the particular plantation site and expected outcomes.

Invariably the widest spacing regimes will produce a higher percentage of wood with higher added value. Plantations with less than 1428 trees per hectare can produce 50% or more of the commercial volume of logs with a SED larger than 25 cm diameter, even in sites of low to medium productivity when subjected to thinnings. However, it is necessary conduct an economic assessment in order to confirm such assumptions as the quantity of volume in absolute terms is small (181–211 $\text{m}^3 \text{ha}^{-1}$) and likely to be economically viable only for small-scale farmers but not for larger commercial enterprises.

As such, it is possible that the application of a light thinning at year 6–7 for initial spacings of 3000 and 2000 trees ha^{-1} and at year 9–10 for the wider spacing treatments would favor the growth of the canopy and trunks of the remaining trees. The thinning at year 12 that occurred at the study site was relatively late for a thinning event and was applied in order to maintain the stand for a longer than the planned span of the experiment; the delayed thinning allowed for the evaluation of dendrometric variables under competitive conditions.

Although there was no difference in the final total volume the modeling shows that there was a potential for harvesting some volume from the two thinning operations, so that greatest volume production was obtained from the densest treatments, although not considering the volume assortments obtained from the different spacing regimes.

Finally, environmental variables, and particularly moisture availability in the soil and the capacity to manage water availability in the forest, must be considered when developing planting and thinning schemes. In this sense, we can assume that initial densities between 1500 to 2000 trees per hectare are most suitable in poor quality sites in order to avoid compromising the soil moisture content.

In this analysis we assess the growth response to various spacing regimes in a full-length rotation (24 years) of a loblolly pine commercial plantation in 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 commercial plantations by providing information about the impact of various spacing and thinning practices on productivity in the long-term.

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