The Crown Ratio and Relative Spacing Relationships for Loblolly Pine Plantation Stands

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EXECUTIVE SUMMARY

The data used in this study come from two designed Culture/Density studies for loblolly pine (*Pinus taeda* L.). A total of 40 installations were established in the southeastern United States during 1995-1998. Each installation contains 12 plots of loblolly pine planted at six levels of density from 600 to 1800 trees/acre in combination with two levels of management intensity, operational and intensive.

The relationship between the crown ratio and relative spacing index is shown to be exceedingly predictable. A model for describing this relationship is developed, and the effects of planting density, site quality, and management intensity on this relationship are investigated with a nonlinear mixed-effects modeling approach.

When loblolly pine plantation stands reach the average live crown ratio of 0.40, a critical point representing a generally acceptable level of tree vigor, their values of relative spacing index range from 0.12 to 0.21, mainly depending on the initial planting density.

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1 INTRODUCTION

Crown ratio (or live crown ratio; CR), is defined as the proportion of the total height of a tree that is covered by live branches. CR is considered to be an indirect measure of a tree's photosynthetic capacity and a measure of stand density. Accordingly, diameter and/or height growth equations in many existing forest growth and yield models use crown ratio as a predictor variable (Monserud and Sterba, 1996; Leites at al., 2009). CR is also a common indicator of tree vigor, and used to determine the timing of and potential response of thinning (Bennett, 1955; Long, 1985; Dyer and Burkhart, 1987). For the southern pines, it is believed that optimum growth and vigor are maintained when a tree has a live crown ration of 0.33 or higher. Thinning is most beneficial for stand growth before the average live crown ratio falls below 0.33 (Demers at al., 2005).

Relative spacing (RS), also known as Hart or Hart-Becking index, is defined as the ratio of the average distance between trees to the average dominant height of stand. With square spacing the ratio is described as $RS = \sqrt{43,560 / N} / H_D$, where N is the number of trees per acre and H_D is average dominant height (ft). RS includes the number of trees and incorporates both site quality and age through dominant height; thus, it has been proposed as a useful measure of stand density for developing thinning specifications for managed plantations (Wilson, 1946 and 1979). Thinning schedules can be determined by setting proper upper and lower bounds of relative spacing. Stand needed to be thinned before the relative spacing reaches the lower bound, and post-thinning relative spacing should not exceed the upper bound. The distance between the upper and lower relative spacing bounds determines the potential thinning yield. The desired upper and lower relative spacing bounds for loblolly pine plantations were set at 0.3 and 0.2, respectively, based on previous research (Zhao et al., 2009).

In practice, there are several indicators of stand conditions that can aid in developing thinning schedules, such as the basal area per acre, crown ratio, relative spacing index, and stand density index (SDI). According to the finding of Long (1985), for several coniferous species, a live crown ratio of 0.40 seems to correspond with an SDI of about 0.50 of the maximum SDI for the species. It is natural to ponder the question - “Are there any predictable relationship among different thinning criteria?” For example, is there a predictable relationship between the crown ratio and relative spacing? Can we infer the crown ratio from the relative spacing, or vice versa?

Previous studies (Harrison and Kane, 2008; Zhao et al., 2008) indicated that both the crown ratio and relative spacing of loblolly pine plantations are influenced by initial planting density and management intensity. The intensively-managed stands have lower crown ratio and relative spacing than operationally-managed stands for the same initial density; both the crown ratio and relative spacing decline with increasing initial density. Crown ratio and relative spacing decrease with age. A relative spacing model for loblolly pine plantations developed by Zhao et al. (2009) indicated that the initial planting density, site index and management intensity affect the development of relative spacing over time. Tree crown ratio models have been developed for several species to estimate crown ratio from tree and (or) stand attributes (Dyer and Burkhart, 1987; Hasenauer and Monserud, 1996; Temesgen et al., 2005). There is relatively little research on the relationship between crown ration and relative spacing, in spite of studies of Kanazawa et al. (1985, 1990). If there is a predictable relationship between crown ratio and relative spacing, is this relationship affected by factors such as initial density, site quality, and management intensity?

The objective of the present study is to examine how the crown ratio is related to relative spacing, using the data from loblolly pine culture and density studies across the southeastern United States. Such relationships and effects of initial planting density, site quality, and management intensity on them are investigated with a nonlinear mixed-effects modeling approach.

2 MATERIALS AND METHODS

2.1 Study Description

The data used in this study come from two designed culture and density studies for loblolly pine installed by the Plantation Management Research Cooperative (PMRC) of the University of Georgia. The Lower Coastal Plain (LCP) Culture/Density Study was established in 1995/96, having seventeen installations in Georgia, Florida and South Carolina across five broad soil groups. The Piedmont and Upper Coastal Plain (PUCP) Culture/Density study was established in 1997/98, with twenty-three installations in Georgia, Alabama, Florida, Mississippi and South Carolina, stratified over seven broad soil classes.

In both culture/density studies, site preparation and subsequent silvicultural treatments were designed to represent two levels of management intensity: Operational and intensive culture. In the Lower Coastal Plain study, the operational treatment consisted of bedding in the spring followed by a fall banded chemical site preparation; the intensive cultural treatment included bedding in the spring followed by a fall broadcast chemical site preparation. The intensive cultural treatment plots also received tip moth control through the first two growing seasons and repeated herbicide applications to achieve complete vegetation control throughout their rotation. At planting, 500 lbs/acre of 10-10-10 fertilizer was applied on all plots. The operation treatment plots were fertilized with the equivalent of 200 lbs/acre of N and 25 lbs/acre of P in the spring of the eighth and twelfth growing seasons. The intensive cultural treatment plots also received 600 lbs/acre of 10-10-10 plus micronutrients and 117 lbs lbs/acre of NH_4NO_3 in the spring of the third growing season, 117 lbs/acre NH_4NO_3 in the spring of the fourth growing season, 300 lbs/acre NH_4NO_3 in the spring of the sixth growing season, and 200 lbs/acre of N and 25 lbs/acre of P in the spring of the eighth, tenth, and twelfth growing seasons.

In the Piedmont and Upper Coastal Plain study, any tillage treatments included in site preparation were carried out on all treatment plots. Both the operational and intensive treatments included a broadcast chemical site preparation. The operational treatment included a first-year banded weed control. The intensive cultural treatment plots received additional herbicide treatments to keep them as completely free of competing vegetation as possible throughout their rotation and received tip moth control through the first two growing seasons. The same fertilizer treatments in the operational and intensive cultural treatment regimes as the Lower Coastal Plain study were applied.

Within both the intensive and operational treatments, six loblolly pine subplots with densities of 300, 600, 900, 1200, 1500 and 1800 trees/acre were randomly located and established in each installation. To ensure the targeted initial density, each planting spot was double-planted and reduced to a single surviving seedling after the first growing season. For detailed information on these two studies such as soils and treatments carried out for each management level, refer to Harrison and Kane (2008) and Zhao et al. (2008, 2009), respectively.

Beginning after the second growing season, biennial measurements of diameters at breast height (Dbh) for all trees and heights (H) on every other tree were made. Heights to the base of the live crown were measured on all trees that were measured for total height. Total heights of unmeasured trees were estimated using a height-diameter equation, $\ln(H) = b_0 + b_1 / Dbh$, fitted to each plot at each measurement age. A tree was considered a dominant tree if it was in the upper 50% of diameters on the plot. Mean crown ratio was calculated by plot from trees with height measurements, and relative spacing index were also calculated by plot.

Base age 25 years site index values were estimated for each installation using the dominant height of the operational treatment plot with 600 trees/acre planting density at the age of the most recent measurement. Site index was calculated using the site index equations developed by Borders et al. (2004) for second rotation loblolly pine plantations. Site indices ranged from 74.8 to 102.6 ft for the LCP culture/density study and from 273.5 to 92.3 ft for the PUCP culture/density study.

After 12 growth seasons 14 of the original 17 installations in the LCP culture/density study were viable; and all 23 installations in the PUCP culture/density study remained after 10 growth seasons. Data from these active installations were used for the analysis reported here.

2.2 General Model for Crown Ratio – Relative Spacing Index

The relationship between crown ratio (*CR*) and relative spacing index (*RS*) of the two loblolly pine culture/density studies is shown in Figure 1. In general, *CR* is positively correlated with *RS*. At early ages, the *RS* is larger and *CR* more closely approaches 1. With stand development, both the *RS* and the *CR* become smaller, approaching 0. That is, crown ratio must be between 0 and 1. This relationship between the *RS* and the *CR* can be described by the following general equation:

$$CR = RS^{\phi_2} / (\phi_1 + RS^{\phi_2}) \tag{1}$$

where ϕ_1 and ϕ_2 are parameters to be estimated.

Figure 1. Relationships between mean crown ratio and relative spacing for loblolly pine in culture/density studies in the Lower Coastal Plain (top) and the Piedmont/Upper Coastal Plain (bottom), by planning density and management intensity.

2.3 Statistical Analysis

From Figure 1, we can see there is high between-plot variability. The general equation (1) is assumed to be common to all plots, but the parameter estimates may vary across plots. Let CR_{ij} and RS_{ij} denote crown ratio and relative spacing at occasion *j* for the plot *i*; ε_{ij} denotes the corresponding residual for CR_{ij}. Thus, the general model is applied to individual plot as

$$CR_{ij} = RS_{ij}^{\phi_{i,2}} / (\phi_{i,1} + RS_{ij}^{\phi_{i,2}}) + \varepsilon_{ij} \; . \tag{2}$$

The between-plot variation is accounted in the model by taking the parameters as mixed effects, with random plot effects $\{b_i\}$. In the first step we didn't consider any covariates on the mixed effects, assuming

$$\begin{aligned} \phi_{i,1} &= \alpha_0 + b_i^{(1)} \\ \phi_{i,2} &= \beta_0 + b_i^{(2)} \\ \begin{pmatrix} b_i^{(1)} \\ b_i^{(2)} \end{pmatrix} &\sim N(0, \boldsymbol{\psi}), \quad \varepsilon_{ij} \sim N(0,\ \sigma_e^2). \end{aligned} \tag{3}$$

Preliminary analysis of the estimated random effects in this case versus planting density, site index and management intensity clearly indicated that both parameters decrease as planting density increases. Both parameters seem to have relationship with site index and management intensity. Thus, in the second step, effects of planting density, site index and management intensity were taken as fixed to both parameters $\phi_{i,1}$ and $\phi_{i,2}$. After that, statistical test indicates that it is not necessary to include random plot effects in the parameter α_i. So the mixed effects model had the following structure:

$$
\begin{aligned}
&CR_{ij} = RS_{ij}^{\phi_{i,2}} / (\phi_{i,1} + RS_{ij}^{\phi_{i,2}}) + \varepsilon_{ij} \\
&\phi_{i,1} = \alpha_0 + \alpha_1 S + \alpha_2 TRT + \alpha_3 (PTPA/100) \\
&\phi_{i,2} = \beta_0 + \beta_1 S + \beta_2 TRT + \beta_3 (PTPA/100) + b_i^{(2)} \\
&\left(b_i^{(2)}\right) \sim N(0,\ \sigma_\phi^2),\quad \varepsilon_{ij} \sim N(0,\ \sigma_e^2),
\end{aligned}
\qquad (4)
$$

where *PTPA* is initial planning density (trees/acre), *S* is site index (ft), and *TRT* indicates management intensity (*TRT* = 1 for intensive culture, *TRT* = 0 for operational culture).

Finally, based on the nature of random effects and structure in (4), the effects of planting density, site index and management intensity on the crown ratio and relative spacing relationship were tested in terms of parameters ϕ_1 and ϕ_2 with the likelihood ratio test (LRT). The model fit, model comparison, and tests were performed using the NLME library by Pinheiro and Bates (2000) for S-plus software, and separately for the data from the LCP and PUCP culture/density studies.

3 RESULTS AND DISCUSSION

In the crown ratio – relative spacing models for both the LCP and PUCP regions, only the parameter ϕ_2 should be taken as mixed effects, after both the parameters ϕ_1 and ϕ_2 include the fixed effects of planting density, site index and management intensity. Based on the model structure (4), the estimates of parameter α_1 were not statistically significantly different from zero in both models for the LCP and PUCP at a significance level of 0.05, indicating that the effect of site index was not significant in terms of parameter ϕ_1. The estimate of parameter α_3 was statistically significantly different from zero in the models for the PUCP, but not in the model for the LCP. That is, in terms of parameter ϕ_1 there was significant effect of planting density in the model for the PUCP, but no significant effect in the model for the LCP. In terms of parameter ϕ_2 , all the effects of planting density, site index and management intensity were significant.

After excluding non significant covariates from the model, we determined and refitted the final model. Parameter estimates of the final model for each of the two culture/density studies are given in Table 1. The plot of augmented predictions indicates that the final models describe the crown ratio – relative spacing index relationship of individual loblolly pine plots well (Figures 2 and 3), and the residual plots (not shown) did not indicate any serious deficiencies in the final models.

Table 1. Maximum likelihood estimates of the parameter, standard errors (SE), and p-values from the final mixed-effects crown ratio – relative spacing index models fitted for the culture/density studies in the Lower Coastal Plain (LCP), and Piedmont/Upper Coastal Plain (PUCP) regions, respectively.

Parameter		LCP			PUCP		
		Estimates	SE	p-value	Estimates	SE	p-value
ϕ_1	α_0	0.04223	0.00225	<0.0001	0.03603	0.00216	<0.0001
	α_2 (TRT)	-0.01922	0.00257	<0.0001	-0.01886	0.00202	<0.0001
	α_3 (PTPA/100)				-0.00038	0.00008	<0.0001
ϕ_2	β_0	2.50091	0.10859	<0.0001	3.43744	0.13016	<0.0001
	β_1 (S)	-0.00411	0.00105	0.0001	-0.01372	0.00130	<0.0001
	β_2 (TRT)	0.34832	0.04776	<0.0001	0.48732	0.05814	<0.0001
	β_3 (PTPA/100)	-0.02552	0.00151	<0.0001	-0.01940	0.00324	<0.0001
	$\sigma_{\phi 2}$	0.06914			0.06104		
	σ_e	0.04599			0.05114		

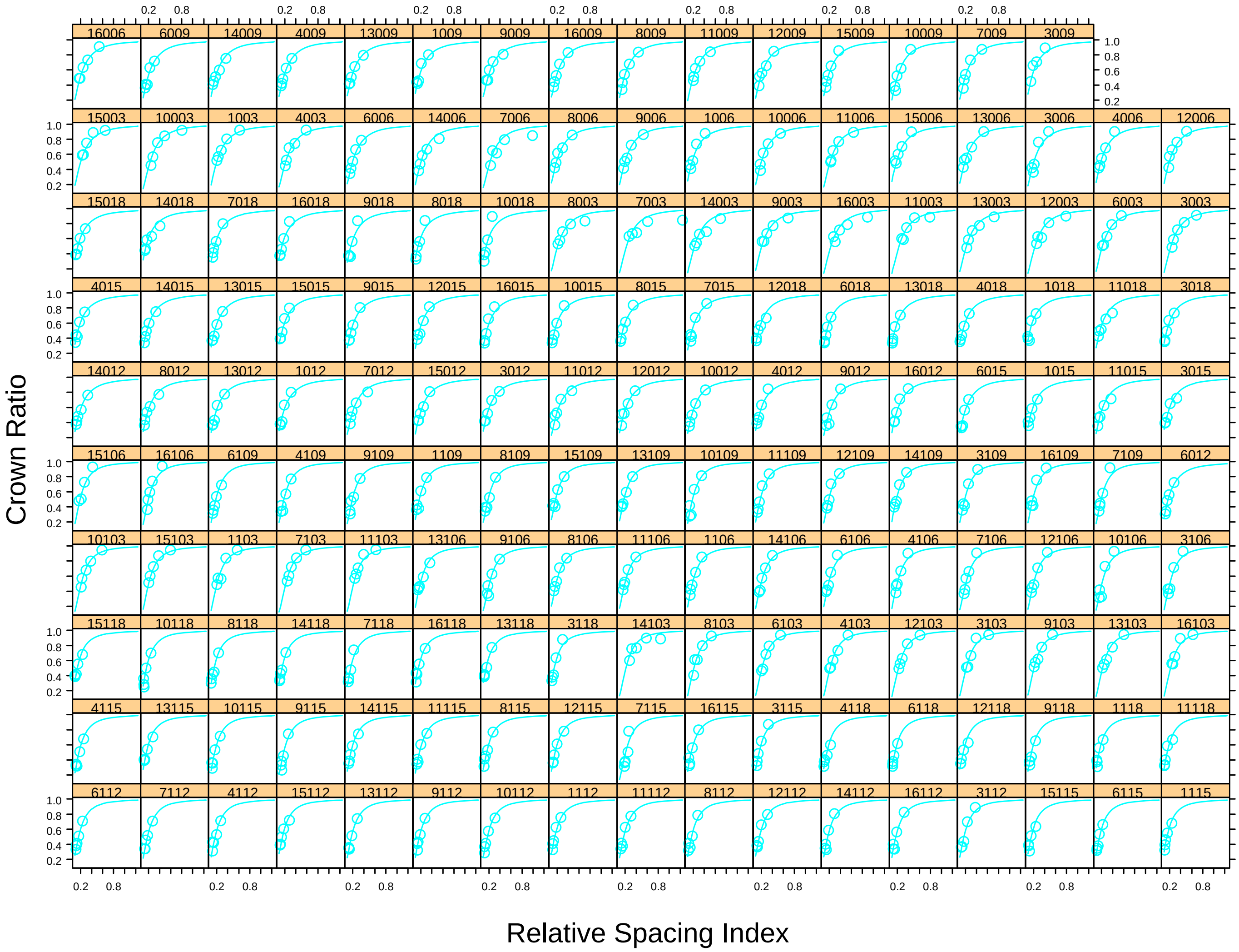

Figure 2. Original data and fitted crown ratio – relative spacing index curves for each plot in the loblolly pine Culture/Density study in the Lower Coastal Plain region.

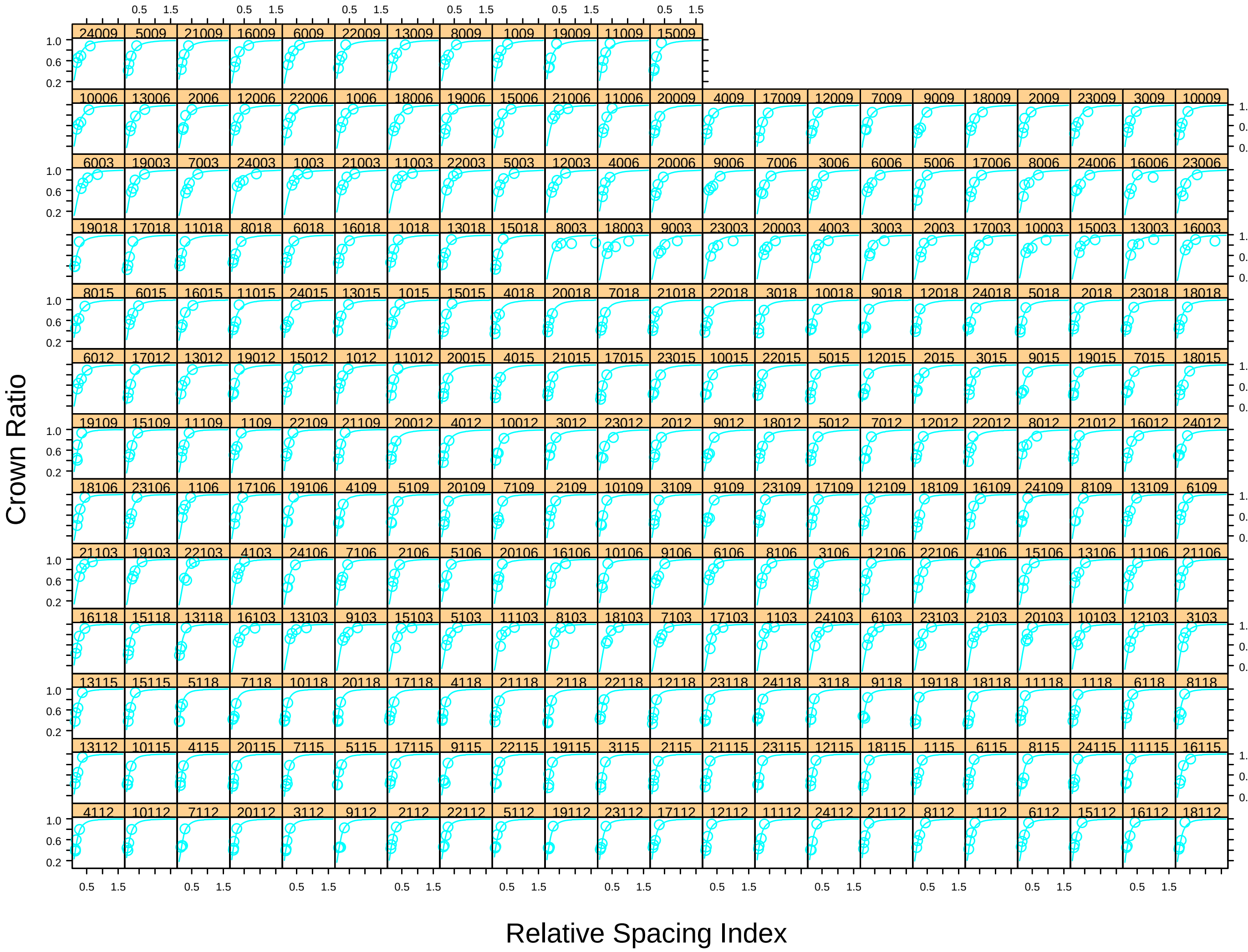

Figure 3. Original data and fitted crown ratio – relative spacing index curves for each plot in the loblolly pine Culture/Density study in the Piedmont and Upper Coastal Plain region.

The crown ratio and relative spacing relationship for loblolly pine plantations was described by

$$
\begin{aligned}
&CR = RS^{\hat{\phi}_2} / (\hat{\phi}_1 + RS^{\hat{\phi}_2}) \\
&\hat{\phi}_1 = 0.04223 - 0.01922 \cdot TRT \\
&\hat{\phi}_2 = 2.5009 - 0.00411 \cdot S + 0.34832 \cdot TRT - 0.02552 \cdot (PTPA/100)
\end{aligned} \tag{5}
$$

for the LCP region; and

$$
\begin{aligned}
&CR = RS^{\hat{\phi}_2} / (\hat{\phi}_1 + RS^{\hat{\phi}_2}) \\
&\hat{\phi}_1 = 0.03603 - 0.01886 \cdot TRT - 0.00038 \cdot (PTPA/100) \\
&\hat{\phi}_2 = 3.43744 - 0.01372 \cdot S + 0.48732 \cdot TRT - 0.01940 \cdot (PTPA/100)
\end{aligned} \tag{6}
$$

for the PUCP regions.

Figure 4 indicates strong effect of initial planting density on the crown ratio and relative spacing relationship for loblolly pine plantations in both the LCP and PUCP. In general, stands planted at higher density will have a larger crown ratio than stands with lower initial planting density when both reach a specific value of relative spacing index. For example, for loblolly pine stands on sites of 80 ft site index under the intensive management regime and with planting densities from 300 to 1800 trees/acre, when their relative spacing decreases to 0.3 the corresponding values of crown ratio ranges from 0.69 to 0.78 in the LCP and from 0.70 – 0.84 in the PUCP; when the relative spacing decreases to 0.2, then the range of crown ratio will be 0.46 – 0.61 in the LCP, and 0.43 – 0.66 in the PUCP.

In both models (5 and 6), the coefficient of site index was significant and included in the parameter ϕ_2. For a given initial planting density and management intensity, however, the effect of site index on the crown ratio and relative spacing relationship is much smaller in the LCP than in the PUCP (Figure 5).

In terms of both parameters ϕ_1 and ϕ_2 in the crown ratio and relative spacing relationship model, the effect of management intensity was significant for both the LCP and PUCP. The pattern of the crown ratio and relative spacing relationship indicates that for given site index and initial planting density this relationship of loblolly pine stands is affected by management intensity mainly before the relative spacing index of these stands decrease to 0.3. As relative spacing index continues to decrease, the relationship between the crown ratio and relative spacing is less affected by management intensity (Figure 6).

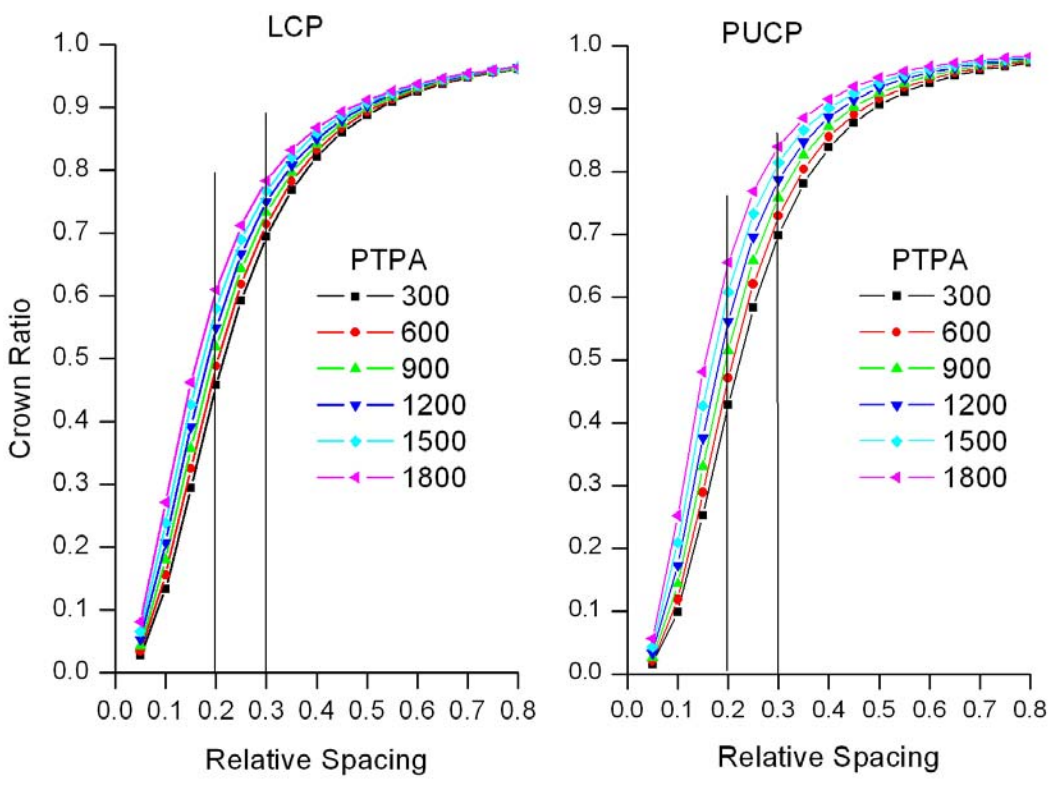

Figure 4.   Crown ratio and relative spacing relationship for loblolly pine stands with six levels of initial planting density (trees/acre) for site index 80 ft under the intensive management regime in the Lower Coastal Plain (LCP) and Piedmont/Upper Coastal Plain (PUCP) regions. Vertical lines indicate upper (0.3) and lower (0.2) bounds of relative spacing suggested for thinning targets and triggers, respectively.

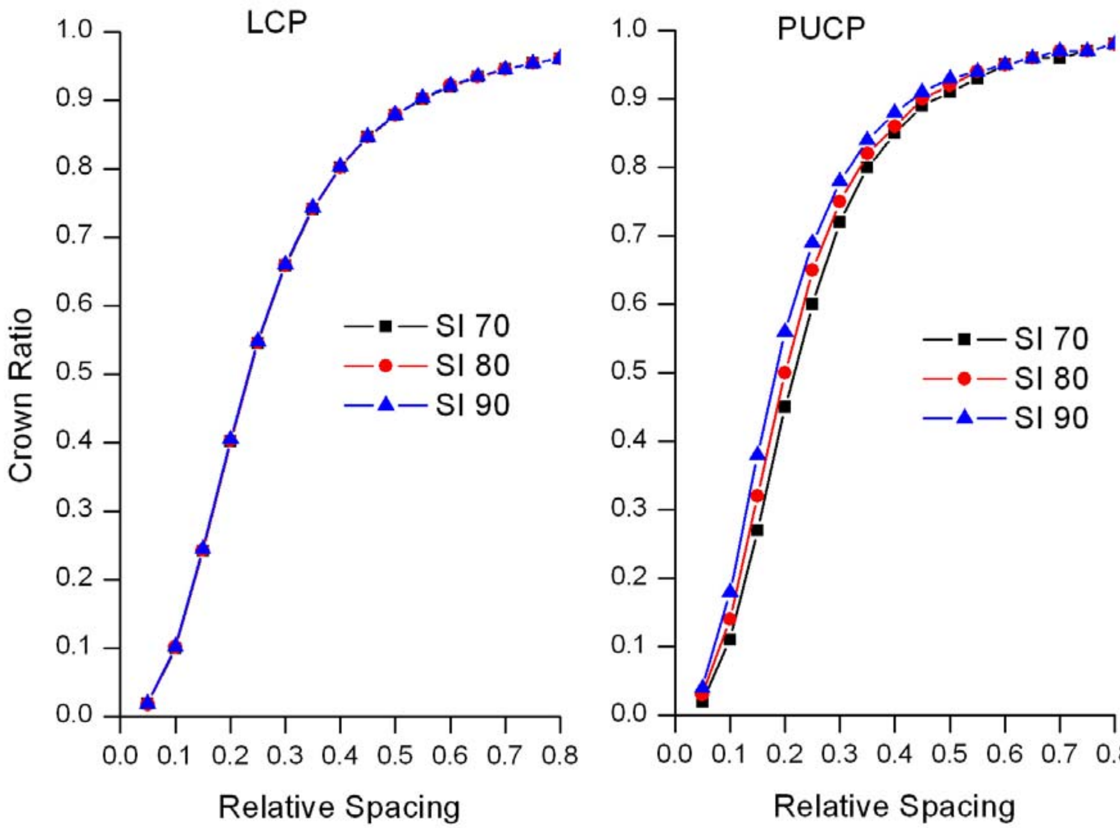

Figure 5. Crown ratio and relative spacing relationship for loblolly pine stands for four levels of site index and initial planting density of 900 trees per acre under the intensive management regime in the Lower Coastal Plain (LCP) and Piedmont/Upper Coastal Plain (PUCP) regions.

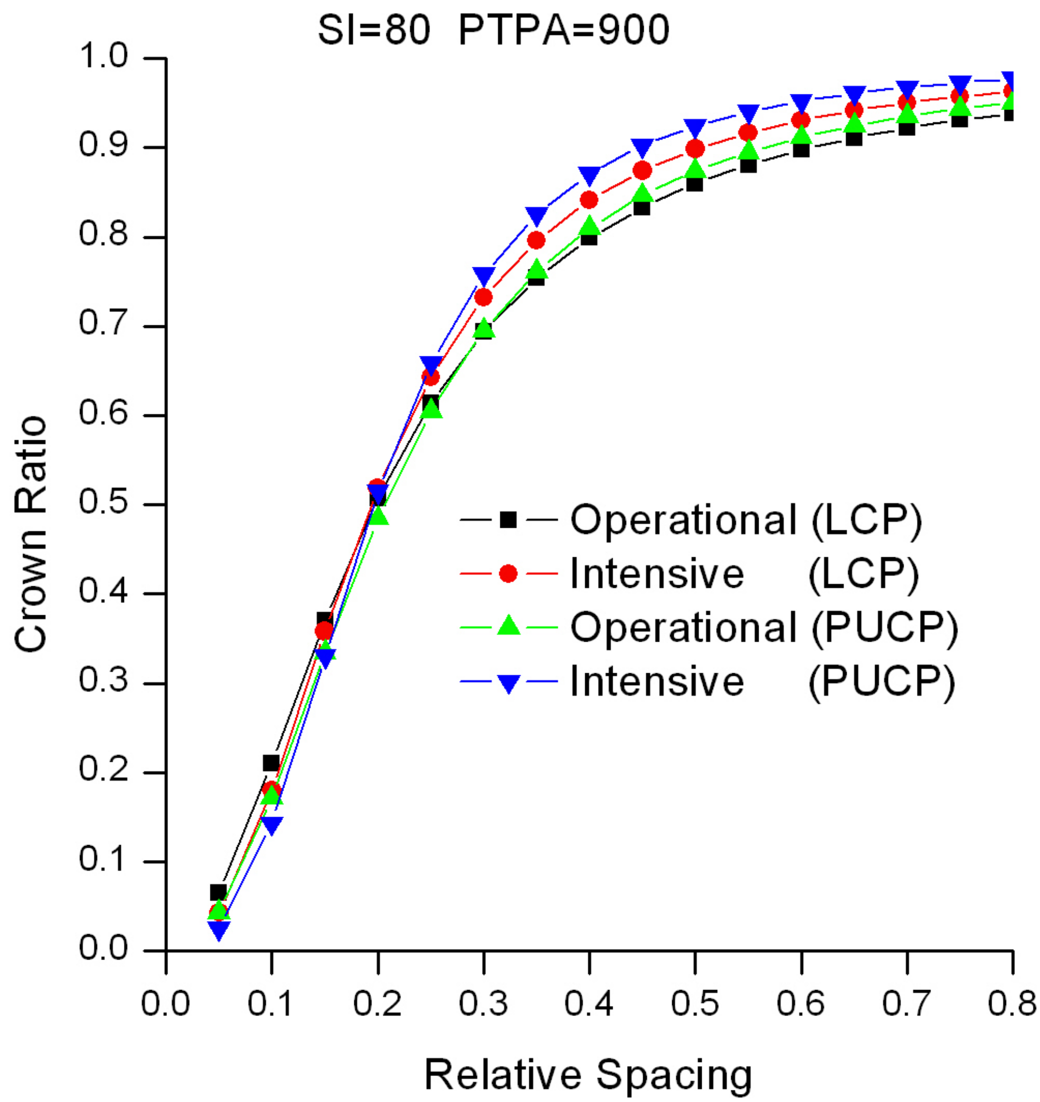

Figure 6. Crown ratio and relative spacing relationship for loblolly pine stands for two levels of management intensity (operational and intensive) in the Lower Coastal Plain (LCP) and Piedmont/Upper Coastal Plain (PUCP) regions for 900 trees/acre planting density and 80 ft site index.

Given the average crown ratio, the relative spacing can be calculated with the model after simple algebraic manipulation: $RS = [\hat{\phi}_1 CR/(1-CR)]^{1/\hat{\phi}_2}$. A crown ratio of at least 0.4 has been cited as presenting a generally acceptable level of tree vigor for number conifers (Long, 1985). When loblolly pine plantations reach average crown ratio of 0.40, our models suggest that their value of relative spacing will range from 0.12 to 0.21, mainly depending on initial planting density (**Table 2**). For the southern pines, it is believed that optimum growth and vigor are maintained before the average live crown ratio falls below 0.33 (Demers at al., 2005). For this point, the corresponding relative spacing ranges from 0.10 to 0.19.

Table 2. Estimated relative spacing when loblolly pine plantations have a crown ratio of 0.40 by physiographic region, planting density, management intensity, and site quality. .

Region	Planting Density	Operational			Intensive		
		SI = 70	SI = 80	SI = 90	SI = 70	SI = 80	SI = 90
Piedmont/ Upper Coastal Plain	300	0.19	0.18	0.18	0.19	0.18	0.18
	600	0.18	0.17	0.16	0.18	0.17	0.17
	900	0.17	0.16	0.15	0.17	0.16	0.16
	1200	0.15	0.15	0.14	0.16	0.15	0.15
	1500	0.14	0.14	0.13	0.15	0.14	0.14
	1800	0.13	0.12	0.12	0.14	0.13	0.13
Lower Coastal Plain	300	0.21	0.19	0.17	0.21	0.19	0.18
	600	0.20	0.18	0.16	0.20	0.18	0.17
	900	0.19	0.17	0.15	0.19	0.17	0.15
	1200	0.18	0.16	0.14	0.17	0.16	0.14
	1500	0.17	0.15	0.13	0.16	0.16	0.13
	1800	0.16	0.14	0.12	0.15	0.13	0.12

Kanazawa et al. (1985, 1990) modeled the relationship between the live crown ratio and relative spacing index for *Cryptomeria japonica* and the relationship between relative maximum canopy depth and relative spacing index for *Pinus thunbergii* in Japan.

The formula in their studies can be derived from the nonlinear model (1) with simple algebraic manipulation. After further logarithmic transformation, the parameters were estimated by the least squares method in the linear regression. In our study, the general relationship between crown ratio and relative spacing index was expressed by the nonlinear model (1), and the parameters were estimated with a nonlinear mixed-effects modeling approach to address the nature of repeated measures. More importantly, we concluded that initial planning density, site quality, management intensity, and physiographic region affect the relationship between crown ratio and relative spacing index for loblolly pine plantations.

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