Crown Ratio and Relative Spacing Relationships for Loblolly Pine Plantations

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Two loblolly pine (Pinus taeda L.) culture/density studies were established in 1995-1998 across the Lower Coastal Plain and Upper Coastal Plain/Piedmont regions of the southern USA. Each installation contains 12 plots of loblolly pine planted at six levels of density from 741 to 4448 trees/ha in combination with two levels of cultural intensity, operational and intensive. The data from 37 viable installations were used to evaluate the crown ratio and relative spacing relationship of loblolly pine plantations. The effects of planting density, site quality, and cultural intensity on the relationship were investigated with a nonlinear mixed-effects modeling approach. The crown ratio and relative spacing relationship is exceedingly predictable. When loblolly pine plantation stands reached the average live crown ratio of 0.40, a critical point representing a generally acceptable level of tree vigor, the corresponding relative spacing index ranged from 0.11 to 0.20, mainly depending on initial planting density. The information about the crown ratio and relative spacing relationship would be useful for selecting the best intensity and timing of thinning.

Keywords: Loblolly Pine; Intensive Culture; Planting Density; Live Crown Ratio; Relative Spacing Index

Introduction

Thinning as a forest management practice is employed in pine plantations for various reasons. For example, the appropriate thinning regimes can reduce density-dependent mortality rates, increase individual tree growth rates, improve product assortment ratios, and enhance spatial and structural uniformity (Newton, 2009). Practically, there are several indicators of stand conditions that can aid in determining thinning regimes, such as live crown ratio (CR), relative spacing index (RS), and relative stand density (RD). CR is defined as the height of the live crown (the part of the tree with live branches) divided by the total height of the tree. CR is a common indicator of tree vigor (Smith, 1988) and used to determine the timing of and potential response of thinning (Bennett, 1955; Dyer & Burkhart, 1987; Long, 1985). Tree vigor and normal rate of diameter growth are maintained as long as CR is 0.40 or greater (Harrington, 2000; Smith, 1988), and ideally a thinning treatment should be scheduled soon after average CR drops below 0.50 (Harrington, 2000). CR also as an indirect measure of a tree’s photosynthetic capacity and a measure of stand density, is used as a predictor variable in many existing forest growth and yield models (Leites et al., 2009; Monsurud & Sterba, 1996).

RS 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 \( RS = \sqrt{10000/N/HD} \), where \( N \) is the number of trees per hectare and \( HD \) is average dominant height (m). 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, 1979). Thinning schedules can be determined by setting proper upper and lower bounds of RS. The desired upper and lower RS bounds for loblolly pine (Pinus taeda L.) plantations were proposed at 0.3 and 0.2, respectively (Zhao et al., 2010).

RD is the ratio between stand density index (SDI) and maximum SDI. For loblolly pine the maximum SDI is 450. Stands begin to undergo density-related mortality (self-thinning) at 0.50 - 0.55 of maximum SDI (Dean & Baldwin, 1993; Drew & Flewelling, 1979). Therefore, thinning should be scheduled when RD reaches 0.45 (Dean & Baldwin, 1993; Harrington, 2000). Because these three criteria (CR, RS and RD) could be considered for selecting the best intensity and timing of thinning, there should be some predictable relationships among them.

In general, both CR and RD decline over time, but they follow different patterns. CR follows an inverse sigmoidal curve. In early years, the CR remains very high, with live branches being retained over nearly 100 percent of stem. As the stand enters the period of total height rapid development the CR decreases rapidly. Then as the stand grows older and the height rate is slowing down, the CR gradually levels at a minimum value. The change of RS over time follows a typical inverse-J trend, which is dependent on the relationship between height increment and mortality (Parker, 1978). In early years, the RS changes are due primarily to height growth. With crown closure the increasing mortality rate plays a more important role, and RS changes are slowing down. Then RS remains constant with a minimum value. For RD, it increases and approaches toward 1 as the stand develops, following a sigmoidal curve. There is a negative relationship between average CR and RD (Long, 1985). Dean (1999) found that average CR decreases linearly with increases in RD for loblolly pine plantations in the West Gulf. He developed a linear model for the CR and RD relationship and used to manage quality objectives. For the CR and RS, there is relatively little research on their relationship, except...
for some work of Kanazawa et al. (1985, 1990).

Previous studies (Harrison & Kane, 2008; Zhao et al., 2008) indicated that the CR declining trend over time is significantly influenced by initial density and management intensity. The CR decrease rate increases with increasing initial density and management intensity. Tree CR models for estimating CR from tree and/or stand attributes have been developed for several species (Dyer & Burkhart, 1987; Hasenauer & Monserud, 1996; Temesgen et al., 2005), but there is no model developed for directly describing the CR change through time. The RS development through time has been modeled for loblolly pine plantations in the southern United States (Zhao et al., 2010). The resulting models indicated significant effects of initial density, site index and management intensity on the RS trend. The intensively managed plots have lower CR and RS than operationally managed plots planted at the same density; with the same management intensity, both the CR and RS decline with increasing initial density (Zhao et al., 2009, 2010). Therefore, if there is a predictable relationship between CR and RS, this relationship is expected to be influenced by initial density, site index and management intensity.

With data from two loblolly pine culture and density studies across the southeastern United States, the objective of the present study is to test the hypothesis that there is a predictable relationship between CR and RS. Moreover, the effects of initial planting density, site quality, and management intensity on this relationship are investigated with a nonlinear mixed-effects modeling approach.

Materials and Methods

Study Description

The data came from two well-designed loblolly pine culture and density studies initiated 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, with 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 LCP 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, 561 kg/ha of 10-10-10 fertilizer was applied on all plots. The operational treatment plot with 1483 trees/ha 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 22.8 to 31.3 m for the LCP Culture/Density Study and from 22.4 to 28.1 m for the PUCP Culture/Density Study. After 12 growth seasons 14 of the original 17 installations in the PUCP culture/density study remained after 10 growth seasons. Data from these active installations were used for the analysis reported.

Model Development

Plot examination of the CR versus RS indicated that CR is positively correlated with RS. While CR more closely approaches I in early ages, the RS is larger. With stand development both the RS and CR become smaller, approaching to their different minimum values. To constrain CR predictions between 0 and 1, the following general equation was used to describe the relationship between the CR and RS:

\[ CR = RS^p \left( \frac{\phi_1 + RS^p}{\phi_2} \right) \]  

(1)

where \( \phi_1 \) and \( \phi_2 \) are the parameters.

Preliminary analysis indicated that both parameters \( \phi_1 \) and \( \phi_2 \) varied across installations and plots. These between-installation and between-plot variations may be accounted in the
model by taking the parameters as mixed effects. Further evaluation that the parameters \( \phi_1 \) and \( \phi_2 \) had some linear relationships with initial planting density \( (N_0, \text{trees/ha}) \), management intensity \( (TRT, \text{a dummy variable indicating the management intensity: } TRT = 1 \text{ for intensive culture and } TRT = 0 \text{ for operational culture}), \) and/or site index \( (SI, \text{m}) \). Thus, the effects of planting density, site index and management intensity were taken as fixed to both parameters \( \phi_1 \) and \( \phi_2 \). After introducing fixed-effects of planting density, management intensity, especially of site index into two parameters, only the plot effects are considered random, denoted as \( [b_i] \), and included in the parameters. Let \( CR_j \) and \( RS_j \) denote crown ratio and relative spacing at occasion \( j \) for the plot \( i; \ e_{ij} \) denotes the corresponding residual for \( CR_j \). Thus, the mixed effects model is applied to individual plot as

\[
CR_j = \frac{RS_{0j} + \phi_{ij}}{\phi_{1j} + RS_{1j}} + e_{ij}
\]

For \( \phi_{ij} = \alpha_0 + \alpha_1 SI + \alpha_2 TRT + \alpha_3 (N_0/100) + b_{1ij}^{(1)}
\]

\[
\phi_{ij} = \beta_0 + \beta_1 SI + \beta_2 TRT + \beta_3 (N_0/100) + b_{2ij}^{(2)}
\]

Thus, the random-effects terms and their corresponding appropriate variance-covariance matrix \( \psi \) in (2) are further identified. Then, based on the final nature of random effects and structure in (2), the effects of planting density, site index and management intensity on the \( CR \) and \( RS \) relationship were tested in terms of parameters \( \phi_1 \) and \( \phi_2 \) with the likelihood ratio test (LRT). The model fit, model comparison, and tests were performed using the NLME library by Pinheiro et al. (2000) for S-plus software, and separately for the data from the LCP and PUCP Culture/Density studies.

### Results and Discussion

In the CR-RS models for both the LCP and PUCP regions, after including the fixed-effects of planting density, site index and management intensity into both the parameters \( \phi_1 \) and \( \phi_2 \), the plot random-effects was no significant on the parameter \( \phi_1 \), but still significant on the parameter \( \phi_2 \). Therefore, only the parameter \( \phi_2 \) was taken as mixed effects. The random-effects variance-covariance matrix \( \psi \) was changed to \( \sigma_{ij}^2 \), that is, \( [b_i^2] \sim N(0, \sigma_{ij}^2) \). SI was not a significant predictor of the parameter \( \phi_1 \) for either of the studies at \( \alpha = 0.05 \). Planting density was significant at \( \alpha = 0.05 \) in terms of parameter \( \phi_1 \) for the PUCP Culture/Density study, but no significant for the LCP Culture/Density study. In terms of parameter \( \phi_2 \), all the effects of planting density, site index and management intensity were significant at \( \alpha = 0.05 \).

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 CR-RS relationship for loblolly pine plantations was described by

\[
\hat{\phi}_1 = 0.04223 - 0.01922 \cdot TRT
\]

\[
\hat{\phi}_2 = 2.50108 - 0.01347 \cdot SI + 0.34832 \cdot TRT - 0.01033 \cdot (N_0/100)
\]

for the LCP region; and

\[
\hat{\phi}_1 = 0.03602 - 0.01886 \cdot TRT - 0.00015 \cdot (N_0/100)
\]

\[
\hat{\phi}_2 = 3.43792 - 0.04503 \cdot SI + 0.48737 \cdot TRT - 0.00786 \cdot (N_0/100)
\]

for the PUCP regions. The augmented prediction plots indicated that the final models describe the CR-RS relationship of individual loblolly pine plots well, and the residual plots did not indicate any serious deficiencies in the final models.

As stands develop, both the CR and RS decrease. Although the changes of CR and RS over time follow different patterns—an inverse sigmoidal curve and a typical inverse-J curve, respectively, the positive relationship between CR and RS can still be described by Model (1). The resulting CR-RS models for loblolly pine plantations in the LCP and PUCP regions, Models (3) and (4), indicated that the relationship between CR and RS is exceedingly predictable.

Our results showed that initial planting density significantly affected the CR and RS relationship for both regions (Figure 1). In general, stands planted at higher density will have a larger CR than stands planted at lower density when both reach a

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCP Estimates</th>
<th>LCP SE</th>
<th>LCP p-value</th>
<th>PUCP Estimates</th>
<th>PUCP SE</th>
<th>PUCP p-value</th>
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<td>( \phi_1 )</td>
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<td>&lt;0.0001</td>
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<tr>
<td>( \phi_2 )</td>
<td>( \beta_0 )</td>
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<td>3.43792</td>
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<td>0.00425</td>
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<td>( \beta_2 (TRT) )</td>
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<td>0.05113</td>
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specific RS. For loblolly pine stands on site index of 24 m and with the intensive management regime, when their RS decreases to 0.3, as planting density increases from 741 to 4448 trees/ha, the CR increases from 0.69 to 0.78 in the LCP and from 0.70 to 0.84 in the PUCP, respectively. When the RS reaches 0.2 the CR ranges from 0.46 to 0.61 in the LCP, and from 0.43 to 0.66 in the PUCP, respectively.

In terms of parameter in the CR-RS model, site index was significant for both regions. For a given planting density and management intensity, however, the effect of site index on overall CR-RS relationship is much smaller in the LCP than in the PUCP (Figure 2). In terms of both parameters $\phi_1$ and $\phi_2$, the effect of management intensity was significant for both the LCP and PUCP. However, further examination of overall CR-RS relationship suggested that, for a given site index and initial density, management intensity strongly affect loblolly pine CR-RS relationship before the RS decreases to 0.2 or before the CR reaches 0.5. During that period, intensively-managed plots will have larger CR than operational plots when they reach the same value of RS. After that period, the CR-RS relationship is less affected by management intensity (Figure 3 and Table 2).

Given the average CR, the RS can be calculated with the model after simple algebraic manipulation, i.e.,

$$RS = \left[\frac{(\phi CR)(1-CR)}{\phi CR} \right]^{\frac{1}{\phi_2}}.$$

When loblolly pine plantations reach average CR of 0.40, a generally acceptable level of tree vigor for numerous conifers (Long 1985; Smith 1988), our models suggested that the RS value will range from 0.11 to 0.20, mainly depending on initial planting density (Table 2). For southern pines, Demers et al. (2005) believed that optimum growth and vigor are maintained before the average CR falls below 0.33. Based on our models, the RS corresponding to 0.33 CR for loblolly pines will range from 0.10 to 0.18. Harrington (2000) suggested that ideally a thinning treatment should be scheduled soon after average CR drops below 0.50 for loblolly pine. The RS corresponding to 0.50 CR for loblolly pines ranges from 0.14 to 0.25.

According to Dean’s model for the CR-RD relationship for loblolly pines in the West Gulf (Dean, 1999), the RD corresponding to 0.40 average CR is 0.63. Using data from our loblolly pine culture and density studies, the negative CR-RD relationship is described by the equation: $CR = 0.9751 - 0.6623RD$. Furthermore, this relationship is not influenced by planting density, site index, and management intensity. Based on this model, corresponding to average CR of 0.4 for loblolly pines in the southern US the RD is 0.87, and corresponding to average CR of 0.5 the RD is 0.72. It was suggested that thinning should be scheduled for loblolly pine plantations when the RD reaches 0.45 (Dean & Baldwin 1993; Harrington, 2000), which corresponds to 0.68 CR. It is obvious that simultaneously considering the CR and RD as thinning triggers may result in different decision on timing of thinning.

$$CR = \frac{1}{\phi CR} - 0.9751.$$

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When calculating the RD for loblolly pines, the maximum SDI is accepted as 450. However, the SDI of some plots in our culture and density studies was actually greater than 450. Therefore, when the RD is considered as one of thinning criteria, choosing the maximum SDI is important.

In summary, there is a predictable relationship between live crown ratio and relative spacing index for loblolly pine plantations. This relationship is affected by initial planning density, site quality, management intensity, and physiographic region.

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