Modelling Inter- and Intra-specific Competition Effects in Loblolly Pine (*Pinus taeda* L.) Plantations.

by

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(ABSTRACT)

Accounting for competition effects is an essential step in building any stand growth simulator. However, accurate modelling of competition effects depends upon a clear understanding of quantitative relationships of various aspects of stand dynamics, including distributional parameters and spatial statistics. This study addressed four aspects of competition effects: 1) competition effects on distributional parameter dynamics of tree size variables; 2) inter-specific (loblolly pine vs. hardwood) and intra-specific competition effects on basal area growth, 3) dynamics of spatial statistical characteristics of DBH and total height, and their relevance to intertree competition, 4) and spatial properties of competition measures by available stand simulators for loblolly pine (*Pinus taeda* L.) plantations. Competition was found to affect the distribution parameters such as coefficient of variation, skewness, and the general shapes of distributions for diameter measurements, total height, crown width and crown height. Competition expedites size differentiation and thereby increases distribution variability for all variables except crown height. Intertree competition also drives skewness of these variables negative, although the distributions of crown heights tends to be more symmetric. Normality assumption generally holds for diameter measurement, but distributions of total height and crown width deviate from, and those of crown height approach, normality with intensified competition. A set of competition driven equations was developed for the distribution parameters and was validated. The differences of distribution parameters among the variables studied could be attributed to their biological meanings. The comparison of inter-specific and intra-specific competition revealed the complexity of competition effects in a mixed stand. The hardwood species studied were more aggressive under higher levels of competition (no-thin and light thin regimes), but almost the same as loblolly pine under lower overall levels of competition (heavy thin regime). The changes of relative aggressiveness of inter- and intra-specific competition across the thinning regimes and over time may have something to do with acclimation of trees to changed habitat and with niche differentiation. The residual analyses on the projection of DBH and total height by TRULOB, PTAEDA2, and PTAEDA2/APA, as well as on observed increments of DBH and total height, indicated that the microsite variations, rather than intertree competition, dominated the spatial characteristics of error structures of projections, pointed out that the incorporation of microsite information would enhance the performance of individual tree growth and stand development simulators greatly from the point of view of the spatial independence of errors. The distance dependent Hegyi type competition index was demonstrated to enhance the spatial accuracy of stand simulators. Spatial autocorrelation patterns for DBH and height were also observed in juvenile loblolly pine stands and found to be results of interaction of microsite variation and intertree competition. After detrending by the trend surface analysis technique, negative autocorrelation statistics were clearly shown to be related to intertree competition. A differential response of DBH and total height toward competition was also discovered in the sense of spatial statistics. Growth in height was far less affected by intertree competition than DBH growth, which further shifted the taper equations for trees under higher levels of competition, and/or trees under inter-specific competition.

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I am indebted to the Loblolly Pine Growth and Yield Research Cooperative and the School of Forestry and Wildlife Resources for their financial support. The Loblolly Pine Growth and Yield Research Cooperative provided data for this study.

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Table of Contents

List of Illustrations

List of Tables

Chapter 1. Introduction

Since the 1950's, large areas have been planted with loblolly pine (*Pinus taeda* L.) in the southeastern United States. An increasing percentage of the total softwood supply is now coming from those plantations. Scientific management of the plantations demands reliable stand growth and yield models, which have been, and are being, developed with varying degrees of success.

Projection of growth and yield demands modelling of the effects of interplant competition and incorporation of this information into the model. Due to environmental considerations and economic constraints, site preparation, planting operations and subsequent silvicultural measures are generally not intensive enough to produce pine monocultures. Some volunteer hardwood species are usually present. Consequently, the pine crop trees of interest not only experience intra-specific competition, but also inter-specific competition. Therefore, efforts are needed to investigate and quantify these two kinds of competition for model building purpose.

The growth of trees depends upon various environmental factors, such as light, water and nutrient elements. These growth resources are often in short supply. Soon after planting, trees compete for the growth factors. It is not unreasonable to assume that the growth of one tree is more or less influenced by the presence of neighboring trees. From the point of view of growth model building, intertree competition complicates the forms of growth models and introduces some subtle statistical complexity into model building. First, individual tree growth is influenced by the presence of its neighbor trees. It is therefore essential that competition be taken into account. Second, the distribution of DBH, height and other tree size variables may be modified by competition, and thereby are temporally dynamic. An assumption of normal distribution or beta type distribution of these variables may not be adequate over all stages of stand development and over all levels of competition. Third, competition processes may generate spatially correlated observations. If spatial autocorrelation exists, it does not matter if it is the result of intertree competition (negative autocorrelation) and/or environmental trends (positive autocorrelation), it would invalidate the assumption of independent observations important for many statistical analyses that are currently used. Such a violation may result in biased estimates of the residual variance and inefficient estimates of the regression coefficients when the method of ordinary least square (OLS) is employed.

It becomes evident that further exploration of the phenomenon of intertree competition is warranted. Not only does investigation on the aforementioned effects of competition dictate the forms of predictive models that will be developed subsequently, but it should also help model builders choose correct model error specifications and corresponding statistical procedures. More importantly, a full understanding of neighborhood tree effects sheds light on many questions about stand dynamics, which is imperative for making management decisions (e. g., the most appropriate site preparation methods, planting density, release treatment regime and thinning schedules).

Chapter 2. Objectives

The objectives of this study were to:

1. Develop models for distributional parameters of tree size variables such as DBH, total height, crown height, and crown width which account for changes over time. Investigate competition effects on tree size variable distribution dynamics.
2. Compare and describe inter-specific and intra-specific competition effects on basal area growth in loblolly pine plantations.
3. Test the significances of spatial patterns of loblolly pine trees on DBH and total height, and examine their relationship with microsite variations and intertree competition.
4. Examine the spatial characteristics of competition measures by available loblolly pine growth simulators, and search for possible means of improving them by studying DBH and total height increment spatial properties.

Chapter 3. Data Description.

Two ongoing projects carried out by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Tech provided the data sets for this study. One project is a thinning study, the other involves spacing trials.

The thinning study consists of permanent plots established at 186 locations throughout the native range of loblolly pine. The plots were installed during the 1980-1981 and 1981-1982 dormant seasons. Plantations used in this study were: at least 8 years old, unthinned, free of evident heavy disease or insect attack, not heavily damaged by ice or wind storm, free of interplanting, unpruned, not fertilized within the last four years, not planted with genetically improved stock, and with at least 494-741 pine stems surviving per hectare which appeared free to grow. No more than 25 percent of main canopy could be composed of volunteer pines. The plantations were established on a cutover area which received "typical" site preparation treatment for the site conditions and time at which the plantations were established. In each qualifying plantation, a set of three comparable but not necessarily contiguous plots was established. Each plot was randomly assigned into a treatment category: (1) control, (2) light thin, or (3) heavy thin. The control plots were generally around 0.1 acre in size while the thinning plots ranged from 0.2 to 0.25 acres. The location and stand history were recorded for each plot. Stand history included the type of stand prior to the current plantation and other pertinent information. In addition, number of trees planted and plantation age were determined. At the establishment of the plots, the following data were recorded for all planted pines: DBH to the nearest 0.1 inch, total height to the nearest foot, height to the base of the live crown, crown class, and a stem quality assessment. The following information was collected for natural pine and hardwoods which were in the main canopy: DBH to the nearest tenth inch, total height to the nearest foot, and species. All measured trees in the main canopy were individually numbered and tagged at breast height. The spatial coordinates of all numbered trees was coded. Natural pine and hardwood trees not in the main canopy, but greater than 0.5 inches in DBH, were tallied by 1-inch DBH classes only (Burkhart 1987).

These plots, which are remeasured with an interval of three growing seasons, had completed three measurements at the time of this study. The data from this study are designated as Coop thinning data for the remainder of this dissertation; these data were used to compare the effects of inter-specific and intra-specific competition on loblolly pine basal area growth (Chapter 5), and to study the spatial characteristics of loblolly pine stand simulators and DBH and total height increments (Chapter 7).

In the spring of 1983, four locations were selected in Virginia and North Carolina for the establishment of spacing trials. Two of these locations were situated in the Piedmont physiographic region and two in the Coastal Plain region. The experimental design chosen was non-systematic, allowing the spacings to vary in each dimension on a factorial basis. This layout created plots of each spacing that vary in size with equal numbers of trees. For this study, a spacing factor (F) of 4 feet was selected and four spacing levels of this factor (1F, 1.5F, 2F and 3F) were incorporated into the design. Each spacing was represented by seven rows and seven columns of measurement trees that form a 49-tree measurement plot. The nearest plots were separated by three guard rows. Thus, each block consisted of sixteen plots developed from the factorial arrangement of the four spacing levels applied randomly to the row and column positions. The sixteen plots in each block were permutations of the four levels. All locations were cutover areas that received an operational chop and burn site preparation treatment prior to planting. At each location, three blocks were established on the most uniform area available.

Because of the low survival rate at the lower Coastal Plain sites, all trees were removed at this location and the three blocks were reestablished in the spring of 1984. Thus, three locations are now in their ninth growing season and one Coastal Plain location in its eighth growing season. Annual measurements were made during the dormant season on all measurement trees. The measurements included groundline diameter (until 1987), DBH (from 1988), to the nearest tenth of an inch; total height, height to the base of the living crown (also referred as crown height), to the nearest decimeter; crown width within the rows, crown width between the rows and maximum crown width, to the nearest foot. In addition, each tree was examined for signs of disease or damage and assigned an appropriate vigor code (Amateis *et al.* 1987).

The data from this study are henceforth designated as Coop spacing data; these data were used to study tree size distribution parameter dynamics (Chapter 4), and the spatial statistical characteristics of DBH and total height with regard to intertree competition and to microsite variations (Chapter 6).

Although most of the variables were measured in the English system, in many cases they were appropriately converted to metric units.

The following terminology and notation was used in this study. In the analysis, all diameters were expressed in centimeters, and heights in meters. However, the units of spacing treatments were in feet.

DBH	Diameter at breast height (1.37 m).
TH	Total height of tree stems.
D	Diameter on a tree stem at ground line.
CH	Height to the base of the living crown.
CW	Mean of between-row and within-row crown diameters in meters.

CCF	Crown Competition Factor, a measure of stand density which is defined to be the sum of maximum crown area, that is, the crown area for an open-grown tree of equal diameter, expressed as a percentage of a hectare.
RS	Spacing index, which is a ratio of the average distance between trees over average height of dominant canopy.
SI	Site index, defined as dominant and co-dominant tree height at age 25 (Burkhart *et al* 1987).
SDI	Stand Density Index, a measure of average stand density that can only be obtained with reference to a predetermined limiting relationship between the number of trees per hectare and the average tree size.
HD	Dominant and co-dominant tree height.
CR	Crown ratio, which is equal to (TH - CH) / TH.
BA	Basal area in m^2 / ha.
CI	Competition index, which varies as to the definition.
CV	Coefficient of variation.
Gini	Gini coefficient, quantifying variable variation, to be defined in the text.
BAF	Basal area factor.
DF	Degrees of freedom.
SS	Sum of squares.
MSE	Mean sum of squared errors.
α	Alpha level. A type I error is made if H_0 is rejected when H_0 is true. The probability of a type I error is denoted by α.
p	P-value. If W is a test statistic, the p-value is the smallest level of significance, α, for which the test indicates that the null hypothesis should be rejected.
Z	A statistic which follows the Gaussian or normal distribution.
F	A statistic which follows the F distribution.
R^2	Coefficient of determination.

Other less often used variables are defined in the text.

Chapter 4. Dynamics of Size Distribution Parameters in Juvenile Loblolly Pine (*Pinus taeda* L.) Stands

Introduction and Literature Review

Genetic variation, microsite heterogeneity, herbivores, parasites and pathogens, *etc.,* can all cause variations in plant size (Benjamin *et al.* 1988, 1986, Harper 1977). However, competition for growth resources may be the most important casual factor in determining the size variation. Therefore, distributions of plant size might be subject to the influences of competition processes, which are the raw material of ecology and evolution theory. It is also of large and increasing economic importance in forestry, agriculture and horticulture, both because the customer requires uniform products, and because variability affects economic yield of tree volume (Benjamin and Hardwick 1986, Salter 1985). Variability of tree size has also special appeal to forest growth model builders, since it is the necessary information for yield prediction by DBH classes (Burkhart 1987).

The standard summary statistics commonly used in ecological and forestry research were the moments of the frequency distribution, i. e., mean, standard deviation, skewness and kurtosis (Naylor 1976). In order to have a comparable index of plant size variability in cases where the standard deviation changes with the mean, Day and Fisher (1937) proposed the coefficient of variation (CV) for population variation. Other variation measures had also been advocated, among which the Gini coefficient (Weiner and Solbrig 1984), which is defined as:

$$Gini = \frac{\sum_{i}\sum_{j}|x_i - x_j|}{2\bar{x}n(n - n)}; \qquad [4.1]$$

X can be any one of the tree size variables;

i = 1, ... n;

j = 1, ... n;

has gained some popularity. Weiner and Solbrig (1984) suggested that the Gini coefficient was particularly appropriate for quantifying invariance in plant communities. Most authors had found that the CV tended to increase with plant density, the phenomenon becoming more pronounced as plants age (Stern 1965, Currah 1975, Edmeades and Daynard 1979, Benjamin 1984, Benjamin and Bell 1985). The CV varied from 7.5% for plants grown in the Pasadena phytotron to 100-200% for the close spaced crops (Benjamin and Hardwick 1986).

The shape of the frequency distribution may also be subject to change due to competition. The normal distribution is often assumed for the sake of convenience and has had wide acceptance. Sometimes logarithmic transformation is used to assure normality. In the forestry literature, the beta type distribution has been widely used for modelling the frequency of DBH (Clutter and Bennett 1965, Bennett and Clutter 1968, Burkhart and Strub 1974, McGee and Della-Bianca 1967, Lenhart and Clutter 1971, Lenhart 1972, Elfving 1974). Perhaps its popularity partially lies in its flexibility for various shapes of distribution and in ease of parameter estimation by the method of moments. No matter what shape an initial distribution may take, it may change unless all trees continuously maintain the same relative growth rate (RGR), which seems to be unrealistic (Cannell, Rothery and Ford 1984, Weiner and Thomas 1986).

Researchers have found that size frequency distribution changes over time. In mature tolerant tree species stands skewed distributions (J-shaped), with many small tree and few large individuals, were documented in the ecological literature (Ford 1975, Waller 1985, Weiner 1985), which showed a striking deviance from the bell shaped distribution in the early stand growth stages. Borough, Gates and McMurtie (1980) studied the skewness of DBH in experimental *Pinus radiata* plantations. A prominent feature of their results, most pronounced in intermediate spacing, was the variation in skewness, which was initially zero, first became negative and later reversed direction, became positive and increased indefinitely, as cited by Gates (1982). In other literature (Koyama and Kira 1956, Rabinowitz 1979) positive skewness was reported. Negative skewness had not been often noted, possibly because researchers did not often have data garnered in the early stages of stand development. Gates and Westcott (1978) showed, mathematically, that a negative skewness should be expected in the early stage of competition. In order to verify his "zone of influence" model, Gates (1982) derived a set of hypothetical growth equations and found that the results from a simulation study of these equations were qualitatively consistent with observations from a *Pinus radiata* plantation. With a spacing experiment in monocultures of *Picea sitchensis* and *Pinus contorta*, intertree competition was reflected in an increased spread in the tree height distribution (negative kurtosis), and in positive skewness of tree diameter (Cannell *et al.* 1984). Most researchers have confirmed that size variability increases over time until the onset of self-thinning.

However, little work had been done relating to the mathematical modelling of competition effects on distribution parameters, especially for stands of juvenile woody plants. Further work in this area would be helpful in understanding plant population competition mechanisms.

Methodology

The Coop spacing dataset was used for this study. The tree size variables analyzed were diameter at ground level (three measurements), DBH (four measurements), total height (eight measurements), crown height (seven measurements) and mean crown width (seven measurements) of the living crown base.

For each plot, mean, coefficient of variation (CV), Gini coefficient (Gini), skewness and kurtosis were computed on all the tree size variables year by year. A Shapiro-Wilk normality test [1] (Shapiro and Wilk 1965) was applied to every measurements of the variables on the plot basis and the corresponding p-values were documented for further analysis.

Based on the mean height of three tallest trees of each plot in the seventh year, site index was determined by the formula of Burkhart *et al.* (1987) , and dominant height in turn was projected for each plot for every year (HD in m). Furthermore, some density measures like number of trees per hectare (N), basal area (BA in m^2/ha.), stand density index (SDI), crown competition factor (CCF), relative spacing (RS) and mean stand crown ratio (CR) (Clutter *et al.* 1983) were computed for each plot for each year.

One of the Coastal Plain planting sites includes data only through the seventh year; this site was set aside for validation purposes. The remainder of the data, including 144 plots and eight remeasurements, were used for statistical analysis and model building. The rationale is that any inferences drawn from one location should be appropriate in another location.

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[1] SAS User's Guide: Basics, Version 5 Edition, SAS Institute Inc., Box 8000, Cary, NC 27511-8000.

Results and Analysis

Dynamics of distributional parameters

If tree size variables can be assumed to be normally distributed, it follows that the second, third and fourth moments of them (variance, skewness and kurtosis) can not be assumed to be normal. Temporal correlation is also inherent with remeasurement data. Therefore, parametric statistical tests or nonparametric models, which are based on either the normality or independence assumptions, or both, can not be applied to test the effects of competition on the distributional parameters of the loblolly tree size variables.

Tables A.1 - A.5 (Appendix A) summarize the distributional parameters of coefficient of variation, Gini efficient, skewness and kurtosis. averaged for each of the planted densities.

Stand mean of tree size measurements

A general linear model was specified to test the effect of stand density over means of tree size measures. The stand age effect was examined as a "within subject factor" by the repeated measurement model[2] (Winer 1971). The model for "between subject factor" was

$$Y = \gamma + \beta + \varepsilon; \qquad [4.2]$$

Where;

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[2] SAS/STAT User's Guide, Release 6.03 Edition, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513

Table 4.1. ANOVA of stand mean of loblolly pine tree size variables

	Stand Age			Stand Density		
Variables[1]	F	DF	p-value > F	F[2]	DF	p-value
GD (cm)	2588.35	4, 130	0.0001	5.45	8, 133	0.0001
DBH (cm)	9451.76	3, 131	0.0001	28.36	8, 133	0.0001
CW (m)	3782.96	6, 128	0.0001	31.28	8, 133	0.0001
TH (m)	5486.78	7, 127	0.0001	0.90	8, 133	0.5197
CH (m)	921.64	6, 128	0.0001	32.20	8,133	0.0001

[1] Where, GD = diameter at ground line.

DBH = diameter at breast height.

CW = average of between-row and within-row crown width.

TH = total height.

CH = height to the base of the living crown.

[2] Wilks' Lambda as incorporated in SAS GLM procedure.

Y	Means of ground line diameter, DBH, crown width, total height, and crown height.
γ	Location effect, assumed to be fixed.
β	Stand density effect. Here densities were the number of trees planted and were treated as a discrete variable so that no prior relationships between density and parameters need to be assumed.
ε	Random error. Since a general linear model with repeated measurement approach was used, there was no time dependence problem. Normality could also be assumed for means of these tree size variables generally by the central limit theorem.

In the juvenile period of loblolly pine development, trees grew rapidly. Means of the five variables showed a very close relationship with stand age (Table 4.1). The variance analyses indicated that the means of DBH, diameter at ground line, crown width, and crown height had a significantly relationship with stand density. However, the observed data showed that the former three variables were negatively, but the last variable was positively, correlated with stand density as expected since competition expedites self pruning. It is worth pointing out that total height was the only variable among the five variables examined which was not significantly affected by stand density (p-value = 0.5197).

Variation of tree size variables

Two measures of tree size variation were used, the coefficient of variation and the Gini coefficient. These two measures did not show much difference in reflecting competition levels either temporally or across the density treatment (Tables A.1 - A.5). Later discussion will focus on the coefficient of variation values only.

As tree grows, the relative variation decreased from the early years for all five size measures (Tables A.1 - A.5). CV of ground line diameter decreased from about 31% at age 1 to 17% at age 5, that of DBH from 26% at age 5 to 14% at age 8 (Figure 4.1), that of total height from 25% at age 1 to 10% at age 8. The values of CV of crown height and crown width declined correspondingly from 48% to 17% and from 35% to 10% (Figure 4.2). Density effects become more marked as stands age as has been observed by others (Stern 1965, Currah 1975, Edmeades and Daynard 1979, Benjamin 1984, Benjamin and Bell 1985). As planting density increased, values of CV of diameter measures, crown width and total height increased correspondingly. Nevertheless, CV of crown height declined with increased planting density.

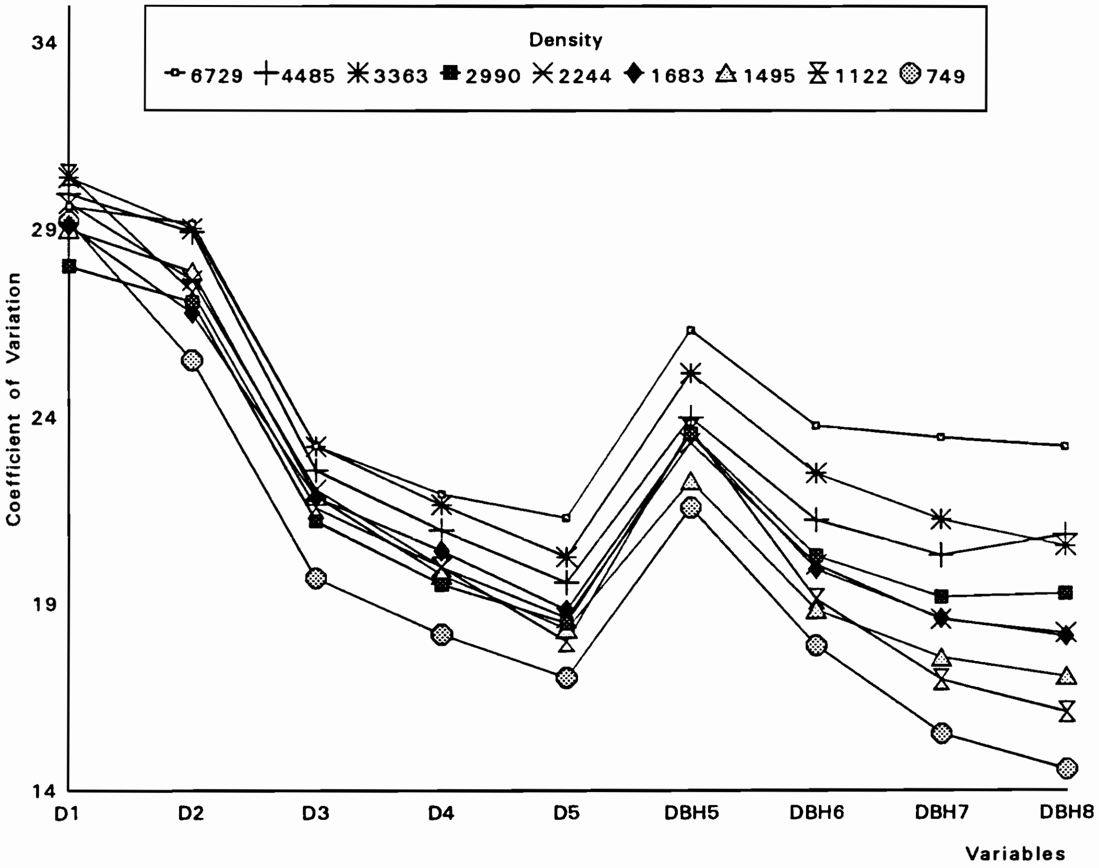

Figure 4.1. Coefficient of variation dynamics of diameter measurements in juvenile loblolly pine (*Pinus taeda* L.) stands: Density is in number of trees per ha. The mean values are illustrated.

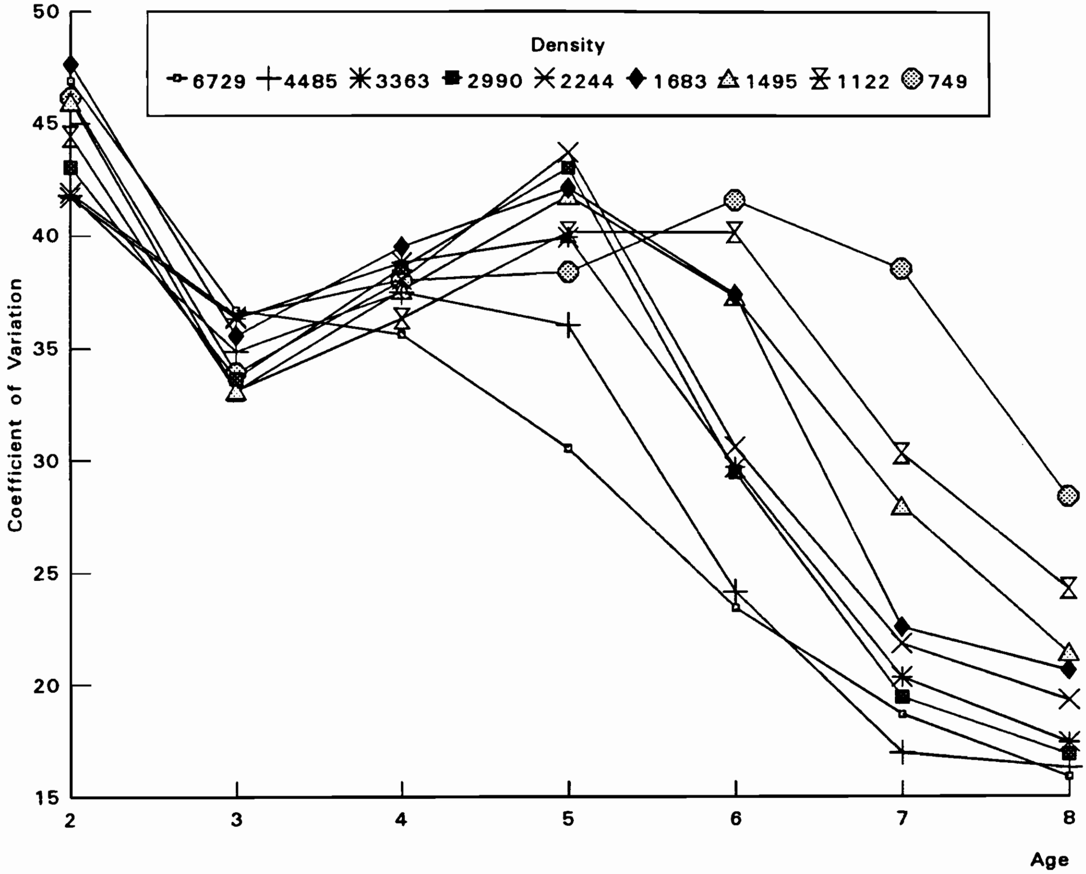

Figure 4.2. Coefficient of variation dynamics of crown height in juvenile loblolly pine (*Pinus taeda* L.) stands: Density is in number of trees per ha. The mean values are illustrated.

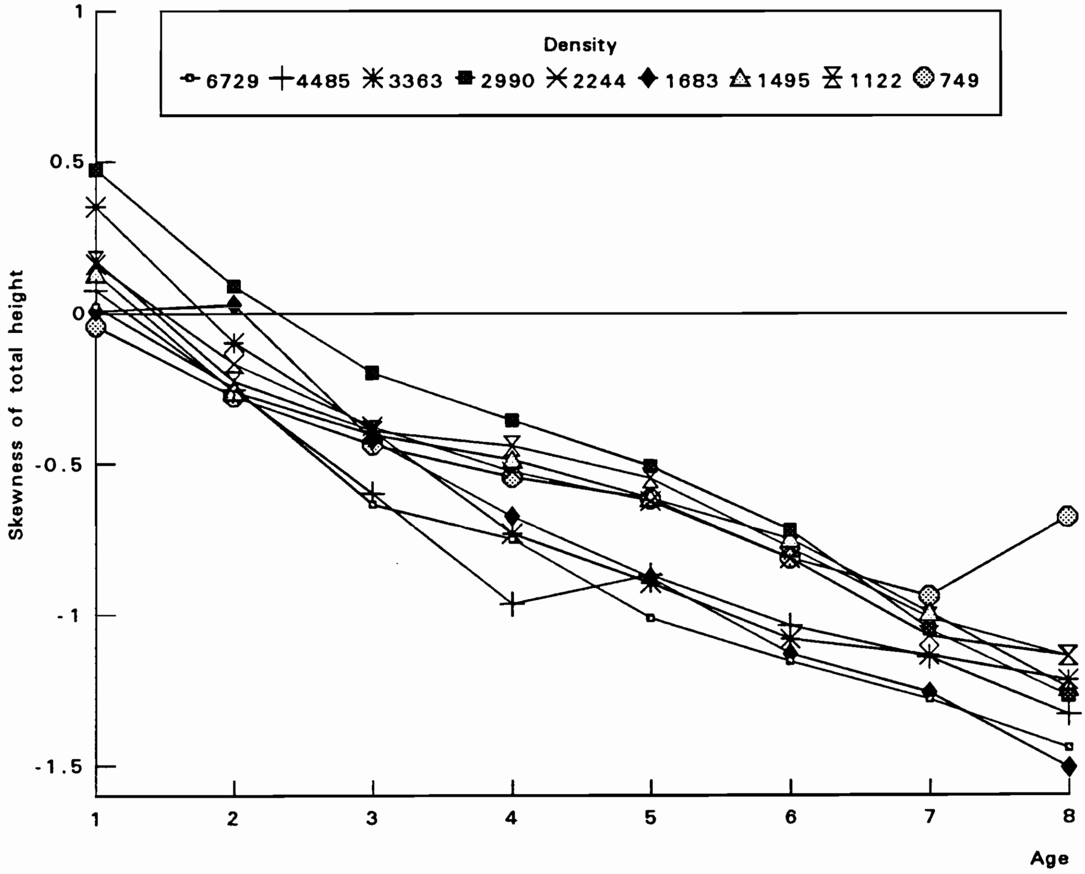

Figure 4.3. Skewness dynamics of total height in juvenile loblolly pine (*Pinus taeda* L.) stands: Density is in number of trees per ha. The mean values are illustrated.

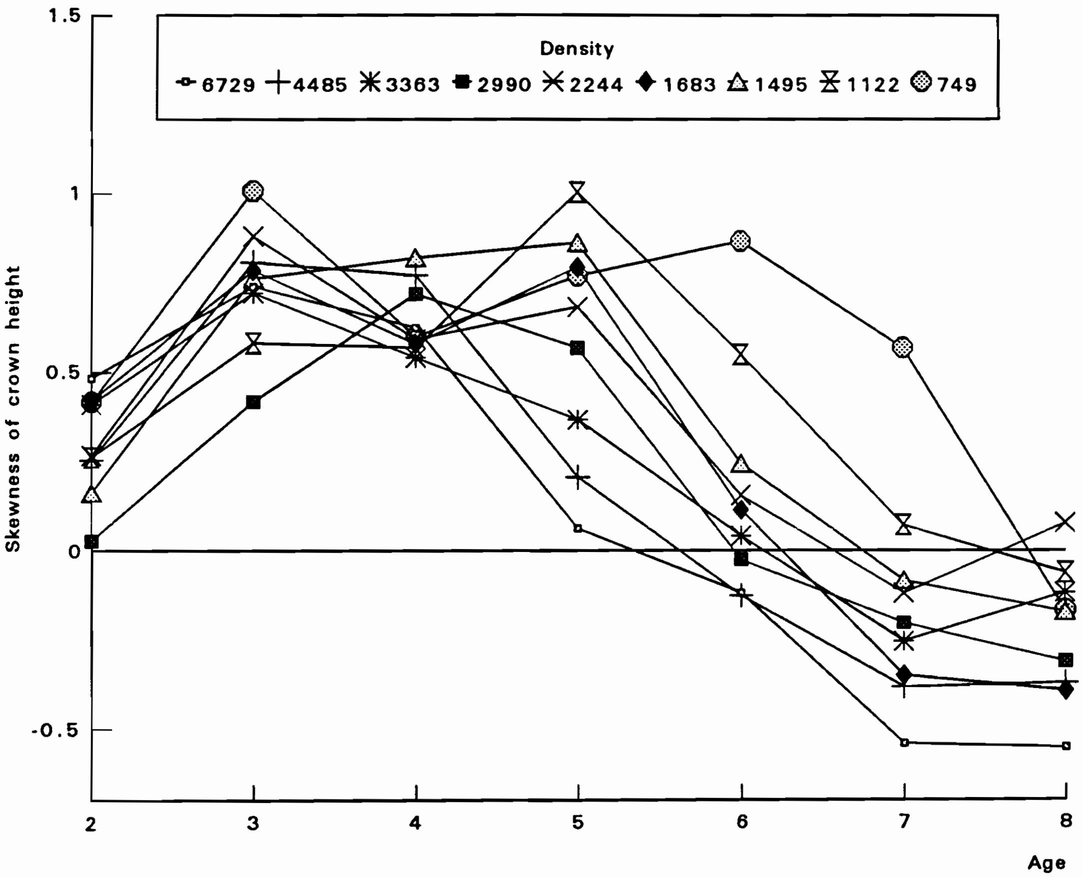

Figure 4.4. Skewness dynamics of crown height in juvenile loblolly pine (*Pinus taeda* L.) stands: Density is in number of trees per ha. The mean values are illustrated.

Distribution skewness of tree size variables

Negative skewness means that there are a few extremely small observations in the left tail of a distribution. Stand growth decreased distribution skewness of all variables examined from a positive, or near zero value, to a more negative value (Tables A.1 - A.5, Figures 4.3 - 4.4). The change from negative to positive value, which was reported by Borough *et al.* (1980), was not observed within the age range of these data, probably because significant self-thinning processes had not yet occurred. Stand density behaved similarly with the values of skewness of total height, crown height, and crown width, declining to a more negative value as the stand grew. Generally for these three variables, the higher the plantation density, the lower the distribution skewness. There was no recognizable trend in the relationship between density and skewness of diameter at ground level and DBH (Tables A.1 - A.5).

Some distinctions can be seen between the dynamics of skewness on crown height and those expressed on total height, crown width and diameter distributions. Among the latter group of variables the values of skewness declined steadily as stands developed (Figure 4.3). The distribution of total height reached a negative value of -1.4 at age 8 where density was 749 number of trees per hectare. At the same density and same age, the distribution skewness was about -0.5 for crown height (Table A.5). More significantly, the values of skewness for crown height tended to remain positive before stands reach the age of six (Figure 4.4), which means that most trees have low crown height, but high total height. The dynamic differences between the distribution skewness imply that trees strive to have a larger photosynthetic volume (large crown ratio) when competition is high.

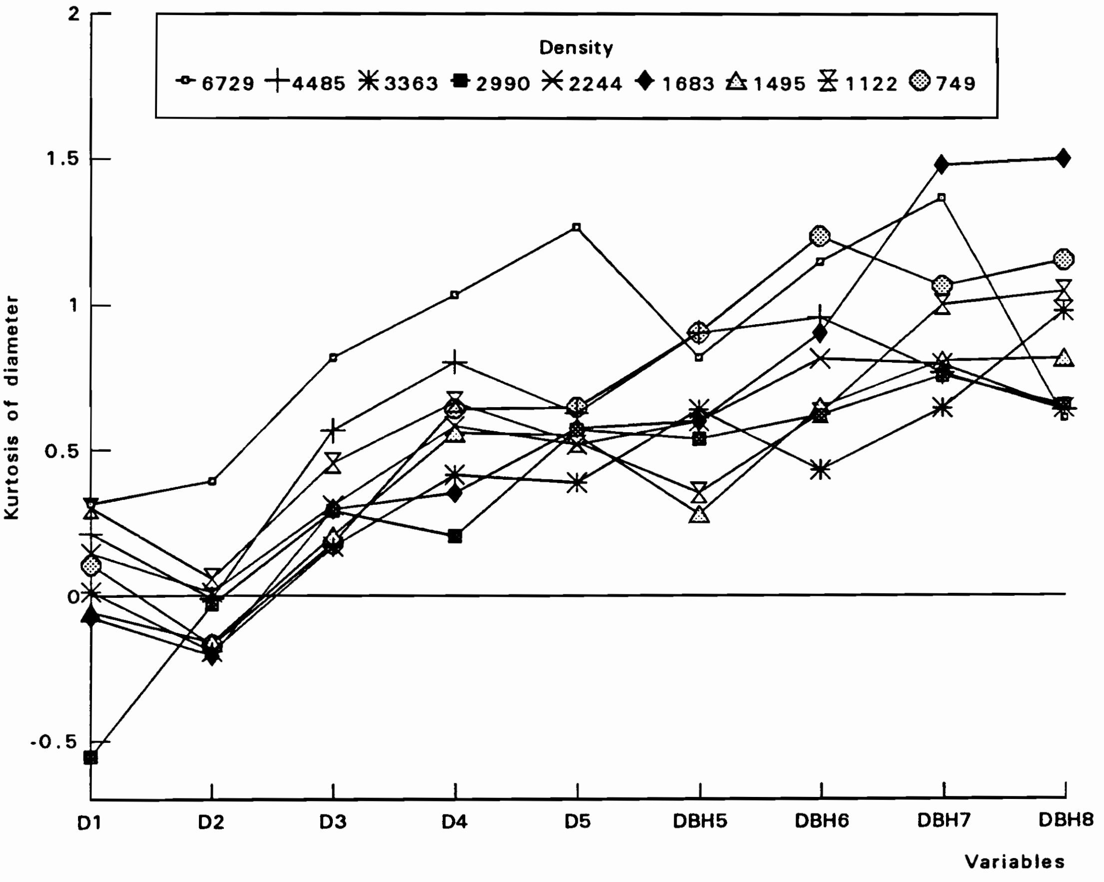

Figure 4.5. Kurtosis dynamics of diameter measurements in juvenile loblolly pine (*Pinus taeda* L.) stands: Density is in number of trees per ha. The mean values are illustrated.

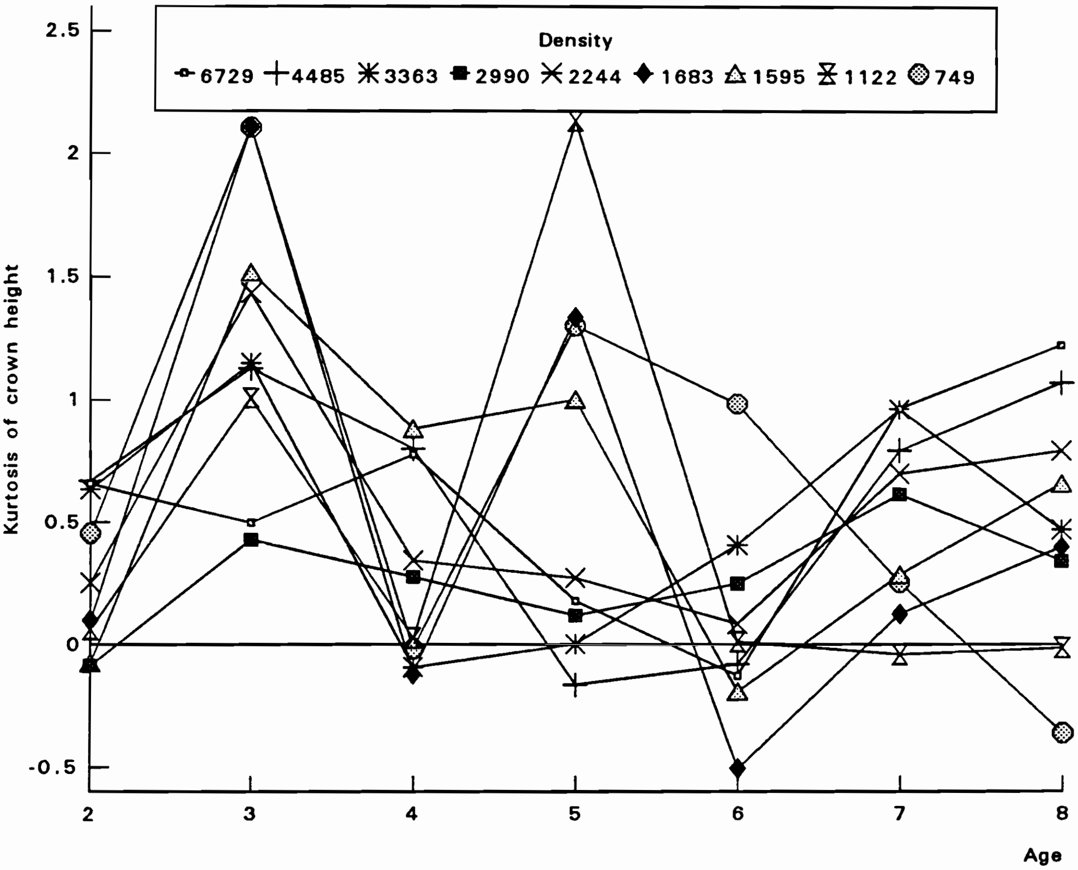

Figure 4.6. Kurtosis dynamics of crown height in juvenile loblolly pine (*Pinus taeda* L.) stands: Density is in number of trees per ha. The mean values are illustrated.

Distribution kurtosis of tree size variables

Kurtosis generally increased with stand age (Table A.1- A.5). At the highest planting density, kurtosis of total height climbed from 0.0178 at age 1 to 3.9912 at age 8, contrasted with what Cannell *et al.* observed. Diameter measures had a narrower range of variation. At the planting density of 6729 trees per hectare, kurtosis of ground line diameter increased from 0.3160 at age 1 to 1.2655 at age 5. Only ground-line diameter and total height were found to have some detectable trends among stand planting densities. It seemed that the denser a stand was, the higher the kurtosis values of total height and diameter measures would be for that stand. The kurtosis of diameters ranges from -0.5 at age 1 to about 1.5 at age 8, and the values of kurtosis on crown height varied a great deal from -0.4 to 2.1 without a recognizable pattern among the planting densities (Figure 4.5 - 4.6).

Distribution normality test on tree size variables

The Shapiro-Wilk normality test was carried out for all five variables. Table 4.2 lists the percentage of plots whose distributions of tree size variables can be assumed to be normal (i. e. the percentage of plots with p-values greater than 0.05).

Based on normality tests on diameter measurement, it seems that the distributions of diameter measurements were not very susceptible to intertree competition. Temporally and across density treatments, the percentage of plots which can be assumed to be normal were quite stable. Except at the first year measurement, normality can be assumed in most cases (40-90%). The noticeable, but not very significant, trend is that the higher the competition, the more normal the distributions of diameter measurements becomes. The results hinted that effects of competition on diameter growth is two-sided (Westoby 1982), where dominant trees and their small neighbors are both influenced.

Table 4.2. Percentage of plots with Shapiro-Wilks normality test p-value > 0.05.

Variables[1]	Density ha^{-1}	n	Plantation Age							
			1	2	3	4	5	6	7	8
GD	6729	9	0	44.4	55.6	66.7	44.4			
	4485	18	0	66.7	77.8	83.3	77.8			
	3363	18	0	66.7	66.7	88.9	66.7			
	2990	9	11.1	66.7	66.7	88.9	66.7			
	2224	36	2.8	69.4	69.4	75.0	80.6			
	1683	9	0	88.9	77.8	88.9	77.8			
	1495	18	0	66.7	77.8	83.3	77.8			
	1122	18	16.7	72.2	72.2	72.2	61.1			
	749	9	11.1	88.9	66.7	55.6	55.6			
DBH	6729	9					66.7	66.7	77.8	88.9
	4485	18					72.2	72.2	88.9	88.9
	3363	18					83.3	77.8	61.1	72.2
	2990	9					77.8	66.7	55.6	66.7
	2244	36					69.4	69.4	75.0	86.1
	1683	9					55.6	44.4	44.4	55.6
	1495	18					77.8	66.7	66.7	72.2
	1122	18					55.6	77.8	66.7	72.2
	749	9					66.7	66.7	77.8	77.8
TH	6729	9	100	88.9	44.4	55.6	33.3	22.2	11.1	
	4485	18	83.3	72.2	72.2	44.4	38.8	33.3	27.8	27.8
	3363	18	72.2	94.1	83.3	61.1	44.4	50.0	38.9	33.3
	2990	9	77.8	66.7	77.8	77.8	77.8	66.7	44.4	33.3
	2244	36	80.6	72.2	80.6	72.2	61.1	44.4	27.8	33.3
	1683	9	100	100	77.8	55.6	44.4	22.2	11.1	11.1
	1495	18	72.2	88.9	77.8	72.2	50.0	44.4	44.4	33.3
	1122	18	72.2	83.3	66.7	61.1	61.1	61.1	38.9	38.9
	749	9	88.9	100	88.9	55.6	66.7	44.4	44.4	77.8
CH	6729	9		11.1	22.2	33.3	66.7	77.8	66.7	66.7
	4485	18		22.2	16.7	22.2	33.3	83.3	66.7	72.2
	3363	18		11.1	27.8	27.8	38.9	72.2	66.7	88.9
	2990	9		22.2	33.3	22.2	22.2	88.9	88.9	77.8
	2244	36		19.4	22.2	36.1	11.1	69.4	69.4	91.7
	1683	9		22.2	11.1	22.2	11.1	44.4	55.6	66.7
	1495	18		27.8	16.7	33.3	5.6	61.1	83.3	77.8
	1122	18		11.1	5.6	38.9	5.6	16.7	72.2	83.3
	749	9		11.1	11.1	33.3	0	0	55.6	100
CW	6729	9		66.7	88.9	66.7	88.9	44.4	44.4	22.2
	4485	18		83.3	83.3	77.8	83.3	50.0	44.4	33.3
	3363	18		83.3	88.9	88.9	77.8	50.0	38.9	27.8
	2990	9		88.9	88.9	88.9	88.9	55.6	33.3	0
	2244	36		83.3	91.7	88.9	88.9	63.9	47.2	0
	1683	9		88.9	88.9	77.8	66.7	77.8	11.1	11.1
	1495	18		100	94.4	94.4	88.9	66.7	66.7	11.1
	1122	18		100	88.9	88.9	88.9	72.2	66.7	27.8
	749	9		88.9	88.9	100	100	67.7	55.6	22.2

[1] Variables defined as in Table 4.1.

The normality tests of total height showed very strong evidence that with increased competition the distribution of total height become less and less normal. At the beginning of establishment, total heights appeared to be normally distributed in the majority of plots. As stands grew, normality can be assumed for distributions of total height in fewer and fewer plots (Table 4.2). This phenomenon was intensified with increased planting densities. The conspicuous distributional difference from the diameter measurements is probably related to the characteristics of height growth. The examination of skewness of total height distribution showed that the high negative skewness was associated with higher intensity of competition, because intense competition resulted in more trees with heights larger than average. Therefore, competition made the distributions of total height deviate from normal.

Crown height distributions approached normality with increased competition (Table 4.2). It seemed that the uniformity of light intensity under a close canopy incurred more symmetric distributions for crown height measurement. Even with the same planting density, but different spacing, the more rectangular spacing treatments would result in more plots where distributions of crown height can be assumed normal than the more square spacing treatments would. For example, at age 7, normality could be assumed for crown height in 100% of plots with spacing 12*4 and 4*12 feet, however, normality could be assumed only in 82% of plots with spacings 6*8 and 8*6 feet. This clearly showed that the intense competition accompanied with the shorter intertree distance in one direction made the distributions of crown height more normal.

The distributions of crown width changed in a similar way to those of total height (Table 4.2). The competition made the distribution of crown width deviate from normality. Therefore, distribution of crown width behaved differently from those of diameter measurements, which hinted that there was no linear relationship between crown width and diameter measurements for stand-grown trees. However, this linear relationship is often assumed for open-grown trees (Clutter *et al.* 1983).

Regression modelling of distribution parameters of loblolly pine tree size with regard to competition levels

The specification of planting density was not adequate to differentiate competition levels since growth rate and mortality would have more important effects after stand establishment. Associating stand parameters directly with competition level would be more helpful in explaining the competition effects.

The previous analyses and plots showed that the distribution parameters were apparently competition sensitive. Preliminary modelling of distribution parameters with various competition measures (N, BA, SDI, CCF, RS, CR) demonstrated that N (the number of trees per hectare) was poorly related to these parameters. BA, SDI and CCF behaved more or less the same; in most cases, BA was the best according to the goodness of fitting with these distribution parameters. However, BA was inferior to RS and CR (average crown ratio of a stand) based on regression coefficient of determination. The appearance of both N and BA in the model enhanced the fitting substantially. So, in the first stage of variable screening, only RS, CR, N and BA were retained for further consideration. Other factors which should be included in the model are site quality and stand age, since the previous analyses already disclosed obvious trends between stand parameters and stand age. Both age and site quality could be expressed by the dominant tree height (HD) to some extent, which in turn could be projected by an appropriate function (Burkhart *et al.* 1987).

Many models were tried to describe parameter dynamics based on these considerations. The following one

$$Y = \beta_0 HD^{\beta_1} X^{\beta_2} + \varepsilon; \qquad [4.2]$$

where;

Y Any one of the distribution parameters;

HD Projected dominant tree height (m) from a site index equation (Burkhart *et al.* 1987).

X Competition measures, RS, CR, or N*BA;

β_i Parameters to be estimated;

ε Random error.

was the best in terms of model flexibility and fitting. The nonlinear regression showed that in most cases CR gave more consistent parameter estimates and produced higher R^2 values than RS and $N \times BA$. Another advantage of using average stand crown ratio is that models for predicting crown ratio or crown height growth are readily available (Short and Burkhart 1992, Dyer and Burkhart 1987). Therefore, the model

$$Y = \beta_0 HD^{\beta_1} CR^{\beta_2} + \varepsilon; \qquad [4.3]$$

was fitted to the coefficient of variation, and the Gini coefficient. For skewness and kurtosis, the model was:

$$Y = \beta_0 HD^{\beta_1} CR^{\beta_2} - 5 + \varepsilon; \qquad [4.4]$$

Equation [4.3] is a monotonic function, and can only model variables with values which are either negative or positive, but not both. Therefore, the inclusion of a constant was necessary for fitting skewness and kurtosis, which could theoretically take any values. The determination of the constant was arbitrary. The value of 5 was chosen only because it was big enough to make the equation suitable for the dataset being analyzed.

Modelling variation of loblolly pine tree size variables

The results of CV and Gini coefficient modelling did not show any practical differences. Considering that the Gini coefficient is more difficult to compute and that it is less useful for stand growth simulators, coefficient of variation was preferred and will be discussed further (Table 4.3).

Table 4.3. Stand CV modelling on loblolly pine tree size variables

		Parameter Estimates[1]				
Variables	n	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\sigma}$	R^2
GD[2] (cm)	720	21.6548	-0.2697	-1.8313	0.4413	0.9622
DBH (cm)	576	102.1574	-1.0482	-1.0284	0.4940	0.9583
Crown Width (m)	1008	33.2437	-0.5065	-0.6064	0.5608	0.9558
Total Height (m)	1008	23.1940	-0.4053	-0.4935	0.6169	0.9442
Crown Height (m)	1008	52.3087	-0.06718	1.7257	0.4978	0.9546

[1] The regression equation is specified in Equation [4.3].

[2] GD = diameter at ground line.

Competition accelerated the size differentiation among trees, which were reflected in the large negative coefficients ($\hat{\beta}_2$) associated with crown ratio in the models for ground line diameter, DBH, total height and crown width (Table 4.3, Figure 4.7). The intertree competition decreased the CV of crown height (a positive $\hat{\beta}_2$), which may be the result of uniformity of low light intensity under a closed canopy. Site quality had a negative relationship with CV, which might suggest that an abundance of growth resources reduces intertree competition.

Modelling skewness of loblolly pine tree size variables

Dominant tree height and intertree competition both decreased skewness of crown width (Figure 4.8) and total height, especially for total height (Table 4.4). Crown width and total height

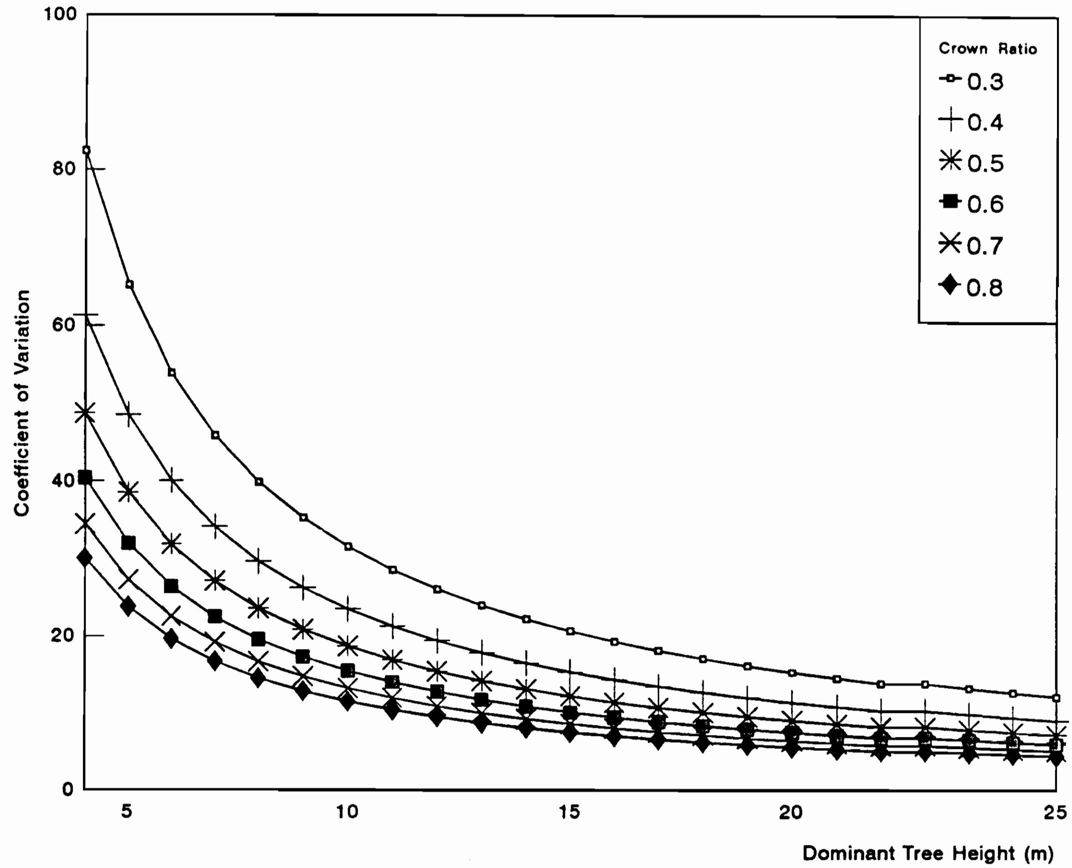

Figure 4.7. Projection of coefficient of variation of DBH: The model is specified in Table 1.3.

Table 4.4. Stand skewness modelling on loblolly pine tree size variables

		Parameter Estimates[1]				
Variables	n	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\sigma}$	R^2
GD[2](cm)	720	4.6937	-0.05023	-0.3014	0.4413	0.9913
DBH (cm)	576	4.8791	-0.02944[3]	0.06211[3]	0.4940	0.9884
Crown Width (m)	1008	5.1457	-0.03494	0.1323	0.5608	0.9864
Total Height (m)	1008	5.0520	-0.08359	0.2496	0.6169	0.9798
Crown Height (m)	1008	5.8701	0.009786[3]	0.4957	0.4978	0.9914

[1] The regression equation is specified in Equation [4.4].

[2] GD = diameter at ground line.

[3] Asymptotic 95% confidence interval covers 0.

are two variables which essentially determine the 'living space' which a tree can occupy. This decreased skewness might result from the fact that light is the primary factor in competition. Whenever intertree competition becomes severe, most trees grow vertically at the expense of DBH growth, and try to expand their living space first. The less competitive trees become shorter and shorter, and will appear in the left tail of tree distributions. The values of $\hat{\beta}_2$ were very small or even negative for ground-line diameter and DBH, probably because competition had less effect on skewness of horizontal growth of tree stem due to two-sided competition (Westoby 1982), or because the interval of observations on DBH was so short (four years) that modelling results became too unstable (large standard deviation for the parameters estimated).

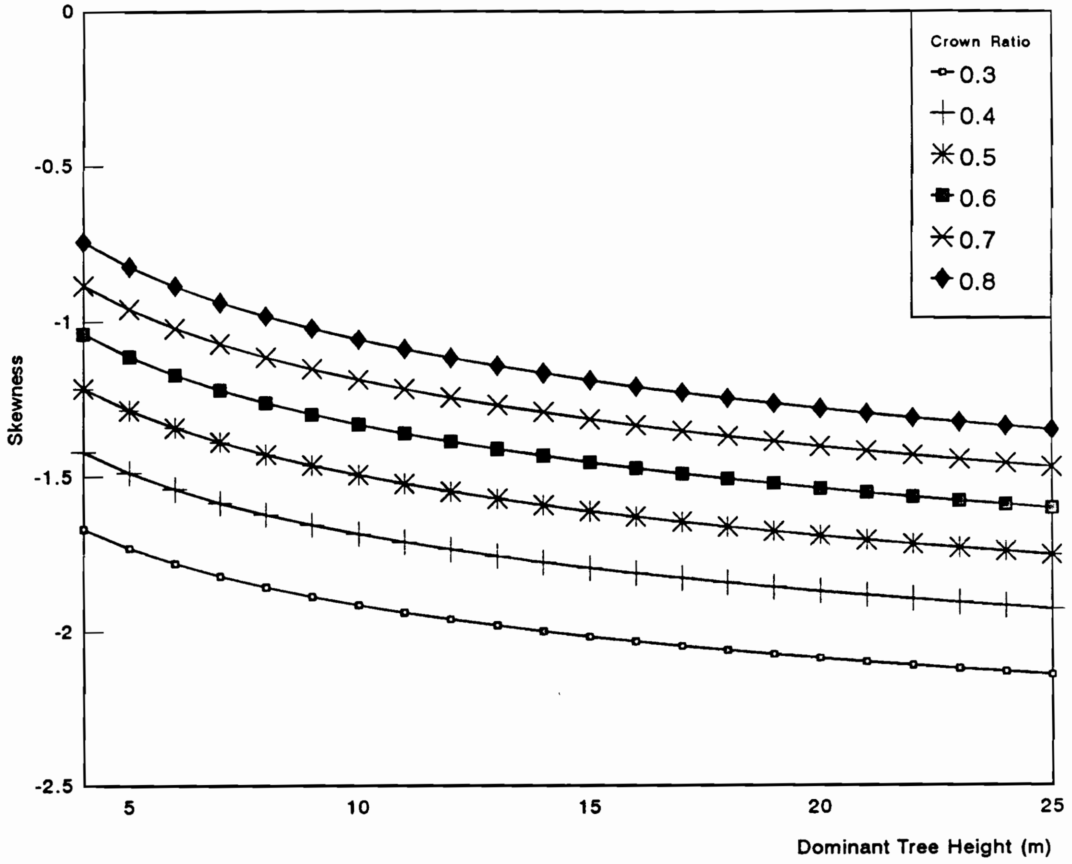

Figure 4.8. Projection of skewness of crown width: The model is specified in Table 4.4.

Table 4.5. Stand kurtosis modelling on loblolly pine tree size variables

Variables	n	Parameter Estimates[1] $\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\sigma}$	R^2
GD^2(cm)	720	5.0966	0.09558	0.2480[3]	1.1257	0.9583
DBH (cm)	576	4.4432	0.1426	0.01196[3]	1.4596	0.9403
Crown Width (m)	1008	4.6562	0.1252	-0.1494	1.7027	0.9203
Total Height (m)	1008	4.6138	0.1687	-0.4693	2.4250	0.8835
Crown Height (m)	1008	5.6079	-0.03146	-0.1164[3]	1.5213	0.9289

[1] The regression equation is specified in Equation [4.4].

[2] GD = diameter at ground line.

[3] Asymptotic 95% confidence interval covers 0.

Modelling stand kurtosis of loblolly pine tree size variables

Kurtosis can be regarded as a measure of distribution "peakedness". If two symmetrical distributions have the same mean and variance, a large kurtosis indicates that the distribution has a long tail and rises to a high and narrow peak (Bulmer 1965). In a practical sense, only the values of kurtosis of crown width and total height (Figure 4.9) were found to increase with increased intertree competition, which hinted that for a stand with a given mean and variance, intertree competition spread the distribution of "living space variables" (TH and CW) even further. In the juvenile period in this study, the kurtosis of tree size measures almost always increased as stands grew

(Table 4.5). Kurtosis of diameter measures and crown height was not found to be significantly associated with the competition measures.

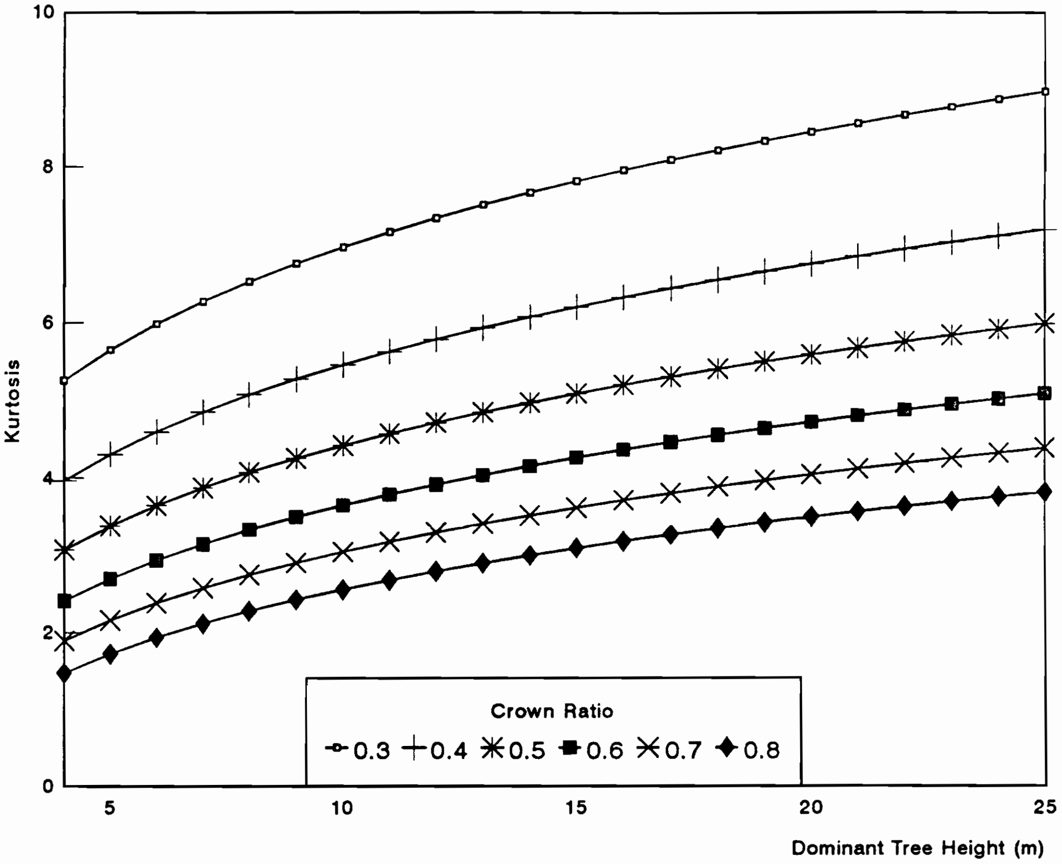

Figure 4.9. Projection of kurtosis of total height: The model is specified in Table 4.5.

Validation of Models.

The models summarized from Table 4.3 - 4.5 were verified using the validation dataset. A relative error was computed for each model of each variable based on the following equation:

$$RE = \frac{Predicted \ - \ Observed}{Observed} \times 100\% \qquad [4.5]$$

And means of absolute values of the relative error are listed in Table 4.6.

Performance of models depended upon which variables or which parameters were to be predicted, and were in accordance with the fitting performances of the previous regression modelling. Predictions for parameters of diameter at ground line level, crown width and crown height distributions were always less precise, probably due to the inaccuracy of their measurement, which might inflate the random error. Models for skewness (an odd number moment) predicted more precisely than the models for CV and kurtosis (two even number moments) (Table 4.6) probably since that regressors are all first moment of variables. Nonetheless, modelling was relatively satisfactory in most cases. Therefore, explanation and inference based on these models were plausible.

Table 4.6. Means of absolute values of relative error of model prediction

Variables	n	CV	Skewness	Kurtosis
Ground Line Diameter (cm)	240	19.83	6.85	13.88
DBH (cm)	192	17.62	7.66	17.51
Crown Width (m)	336	16.96	10.02	15.69
Total Height (m)	336	22.54	8.51	19.41
Crown Height (m)	336	18.16	10.62	20.37

Conclusions

In this studies, data collected from a spacing trial over a eight-year period were analyzed. Therefore, continuing studies are necessary for understanding of tree size distribution dynamics over a whole stage of stand development. Some modification of models may be needed to predict population parameters in mature stands. Nonetheless, the growth models developed in this study may be incorporated into stand simulators. The preliminary statistical analysis and modelling of spacing study data may lead us to the following conclusions about the parameter dynamics of size distributions in juvenile loblolly pine stands:

1. The distribution parameters of tree size depended upon competition level and stages of stand development. It was possible to predict tree size distribution parameters by competition measures. The results of validation demonstrated that the models developed in this study were relatively precise and usable.
2. Intertree competition increased variation of ground-line diameter, diameter at breast height, crown width and total stem height, but decreased the variation of crown height in juvenile loblolly pine stands. The abundance of growth resources in a good site reduced competition effects to some degree. Temporally, coefficient of variation declined as stands aged for all tree size variables examined.
3. Higher levels of competition made distributions of total height, crown width and crown height more negatively skewed, and had the same effect for those of DBH and ground-line diameter to a lesser extent. Therefore, competition made the majority of trees fairly tall, but a few extremely short. This phenomenon will likely become more pronounced before significant mortality occurs. Notwithstanding, the skewness of crown height tended to stay positive longer than for other variables.

4. Competition increased distribution kurtosis of total height, crown width and crown height as stands grew, but had no substantial effects on the kurtosis of DBH and ground-line diameter distributions.
5. Significant effects of competition could be more easily recognized on the third and fourth moments of variables like total height, crown width and crown height, than on those of diameter measurements. The former group of variables determine the 'living space' for a tree, and therefore its capacity for resource acquisition. It may be inferred that competition processes differentiated the living spaces of trees first. Larger negative skewness and positive kurtosis values meant that a distribution had a few very small values given the same values for mean and variance, which became smaller and smaller with increased levels of competition. This differentiation preceded the onset of self-thinning processes.
6. The shapes of tree size distributions were found to be subject to change due to competition for variables like total height, crown height, crown width, and stable for variables of diameter distributions. Normality was an acceptable assumption for distributions of diameter measurements in juvenile loblolly pine stands. However, the distributions of total heights generally became less normal as stand grew and as competition intensified. It may be inferred that competition effects are more two-sided on diameter growth, which confirms the study with monoculture of red pine (*Pinus resinosa* Ait) (Brand and Magnussen 1988), but more one-sided on total height growth. That is to say, both larger and smaller neighbors affect each other on diameter growth, while only larger neighbors affect smaller one on total height growth, not vice versa (Westoby 1982). The distributions of crown height approached normality with increased competition, which was coincident with smaller variation and smaller skewness. It seemed that the uniformity of light condition under a closed canopy led distributions of crown height to approach normal. However, the competition polarized the distributions of crown width, which became more and more deviant from normality with increased competition.

Chapter 5. Inter- and Intra-Specific Competition Modelling in Loblolly Pine Plantations (*Pinus taeda* L.) on Cutover, Site-Prepared Lands

Introduction and Literature Review

In relative terms, growth and yield modelling research has focussed on intra-specific competition, while little attention has been paid to inter-specific competition. One reason might be that most researchers focused attention on monocultures since they are very productive and economically desired. Moreover, modelling inter-specific competition is much more complicated, involving testing more hypotheses and estimating more parameters. However, information about inter-specific competition is earnestly needed even for modelling artificially regenerated monocultures, for example, loblolly pine plantations, since some hardwood species are generally present. It should be pointed out that the stand structure of such a plantation is fairly simple compared to that of naturally regenerated mixed stands, or stands that are planted and receive little or no hardwood control.

Traditionally, two experimental designs have been employed to study the growth of mixed populations (Harper 1977). One is additive, where species A was sown at a standard density and species B was sown with it at a range of densities. This experimental design has a marked relevance to loblolly pine plantations under study in which hardwoods are invading. Another is called the substitutive design. In this design the replacement series are arranged to involve sowing two species in varying proportion while maintaining a constant overall density. Both methods need designed experiments; the models developed from them do not have much applicability for retrospective studies on survey data.

Neighborhood approach and its variations have been used very successfully in studying the relationship between woody plant growth and vegetative competition (Simard 1990a and 1990b, Zutter 1991). Basically, this approach attempts to associate the plant growth with various measures of neighborhood competition, such as competitive vegetation cover, or competition indices. Simard applied this approach in his research on competition between Sitka alder (*Alnus sinnata viridis spp.* (Reg.) Rydb.) and lodgepole pine (*Pinus contorta var. latifolia* Dougl.), and between paper birch (*Betula payyrifera* Marsh.) and planted Douglas-fir (*Pseudotsuga menziesii var. glanca* (Mirb.) Franco.) (Simard 1990a and 1990b.). He found that alder cover below 10% actually benefited lodgepole pines and that Douglas-fir performance was substantially enhanced with decreased neighboring birch density. He also identified the ecological competition thresholds for Douglas-fir and for lodgepole pine growth, around which competition relationships change.

Using the neighborhood approach, Mack and Harper (1977) analyzed data collected from a very sophisticated experiment involving five short-lived dune annuals in a substitutive experiment. The measurements made on individual plants together with their position (x, y coordinates) were analyzed to determine: (a)the varying aggressiveness of the species; (b)the distance between each plant and (c) the spatial dispersion of the most competitive neighbors around each other. The aggressiveness of each species was measured as the average depression it caused on the other four species compared with their growth in pure stands. A competition model was developed and up to 69% of the variation in weight of one species was accounted for by the model that considered a subject plant's first, second and third degree (defined by their position in rings with increasing diameters) neighbor's size, distance, spatial dispersion patterns and species.

Although neighborhood approaches provide models for competition interaction studies, some efforts have to be made to link information from the competition studies to forest growth and yield modelling processes. Burkhart and Sprinz (1984) investigated the effects of hardwood on loblolly pine survival, growth and yield. The approach taken to model hardwood effects on yield was to regard values observed in old-field plantations as upper limits and to compute reduction factors based on the level of hardwood competition. The research showed that height-age development, height-DBH curves, individual tree volume relationships, and diameter distributions were significantly different between the data sets on old-field (negligible hardwood competition) and on cutover sites (with varying degree of hardwood composition), which implied certain effects of hardwood competition. However, their attempts to relate those differences to the level of hardwood competition failed except in the analysis of diameter distributions. The pine survival equation developed from the dataset of the old-field plantations was modified by a reduction factor related to the percentage of total hardwood basal area in the main canopy. The Burkhart and Sprinz model showed close agreement with plot observations from the hardwood conversion/site preparation study in Fayette county, Alabama (Whipple and White 1965). A RYT (Relative Yield Total) value (Harper 1977) was computed based on the Fayette study. The average RYT value for the data at age 11 was 0.75; at age 24 the average was 0.80. These values implied mutual antagonism, which were supported by the fact that the decrease in pine basal area and volume was greater than the proportional increase in hardwood basal area.

Competition research has resulted in several laws of population dynamics such as the final yield law and the reciprocal law. These laws, in turn, can advance our understanding of competition processes. Joliffe *et al.* (1984) made use of the constant yield law to develop the synthetic no-interaction responses from monoculture experiments which were compared with results from mixed stands. Thus intra- and inter-specific competition effects could be separated and measured. Spitters (1983) took another approach by making use of the reciprocal yield (W) model:

$$1/W = \beta_0 + \beta_1 N \qquad [5.1]$$

and the assumption of additive competitive effects (both intra- (β_{ii}) and inter-specific (β_{ij})):

$$1/W_i = \beta_{0i} + \beta_{ii} N_i + \beta_{ji} N_j \qquad [5.2]$$

In this model the reciprocal of average plant weight ($1/W_i$) of species i was described by its own density (N_i) and by the density of a second species (N_j). Intra- and inter-specific competition effects were quantified by the coefficients β_{ii} and β_{ji}, respectively. He illustrated his method with a set of data from maize (*Zea mays* Linn.) and groundnut (*Arachis hypogaea* Linn.) grown in mixtures and monocultures at different total densities. The fittings were outstanding for both maize ($R^2 = 0.99$) and groundnut ($R^2 = 0.86$). The coefficients estimated indicated that intra-specific competition was greater than inter-specific competition and maize itself was a 6.9 times stronger competitor towards maize than groundnut. By manipulation of these coefficients the author postulated that a certain niche differentiation existed between those two species. However, some caution should be exercised in explaining these coefficients since they may be related.

In addition to the conventional analysis of replacement series experiments, Roush *et al.* (1989) used the synthetic no-interaction approach and the reciprocal yield law model to describe competitive interaction between wheat (*Triticum aestivum* Linn.) and Italian ryegrass (*Lolium italicum* A.). He concluded that the conventional analysis was least sensitive in describing the influences of either density or proportion on the plant association. The synthetic no-interaction approach provided the most detailed analysis of the influence of proportion on the species interaction. The reciprocal yield approach provided the simplest and the most sensitive analysis of the joint influences of density and proportion. The latter approach also provided the most quantitative information for interpreting plant competition.

An alternative model of the reciprocal yield law (Harper 1977) is:

$$W = \beta_0 N^{-\beta_1} \qquad [5.3]$$

which can be transformed to a linear form by taking the logarithm of both sides, giving:

$$\log(W) = \log(\beta_0) - \beta_1 \log(N). \qquad [5.4]$$

When analyzing yield-density relationships in experimental stands of Douglas-fir and red alder (*Alnus robra* Bong.) seedlings, Shainsky and Radosevich (1991) amended Equation [5.4] as follows:

$$\log(W_i) = \log(\beta_{0i}) - \beta_{ii} \log(N_i) - \beta_{ji} \log(N_j) \qquad [5.5]$$

without explicitly stating any assumptions. Equation [5.5] can be transformed back into the exponential form as:

$$W_i = \beta_{0i} N_i^{-\beta_{ii}} N_j^{-\beta_{ji}} \qquad [5.6]$$

The multiplicative competition effects implied by this model are difficult to interpret. They introduce additional difficulty into the explanation of parameters since intra- and inter-specific competition can not be separated due to the intrinsic properties of this model. Therefore, any comparison of competitive advantage according to regression coefficient estimates, and further inference based on this comparison may be misleading.

Statistically speaking, Equation [5.2] and Equation [5.5] were transformations to models that are linear in the parameters. Therefore, another possibility could be:

$$\log(W_i) = \beta_{0i} - \beta_{ii}N_i - \beta_{ji}N_j; \qquad [5.7]$$

which implies additive competition effects and no interaction as does Equation [5.2].

Competitive interactions of conifers, shrubs and herbs have also been documented. White and Newton (1988) established whiteleaf manzanita (*Arctostaphylos viscida* Parry.) at densities ranging from 0 - 27,000 seedlings/ha in 2-year-old mixed stands of Douglas-fir (*Pseudotsuga mensiesii* (Mirb) Franco.) and ponderosa pine (*Pinus ponderosa* Doug. ex Law.). They employed analysis of variance, regression and general linear regression models to study various forms of both intra- and inter-specific interactions. They found that intra-specific competition in manzanita was occurring by age 5, which was before the occurrence of full site occupancy. During the early stage of stand development, it was herbs, not conifer species, that had a significant negative impact on manzanita growth. Stem volume of 5-year-old conifers was recorded in relation to manzanita density, biomass, leaf area index and canopy volume.

Ek and Monserud (1974) developed an individual tree based computer model for simulating the growth and reproduction of mixed forest stands. No inter- and intra-specific competition models or mechanisms were explicitly specified. However, their competition index formulas implicitly assumed that both intra- and inter-specific interactions are asymmetric and two-sided. The extent of competition from a neighbor was determined to a degree by shade tolerance of host trees, which was determined empirically. Nonetheless, the quantitative relationships about inter- and intra-specific competition effects on tree growth are needed to be incorporated into stand simulators. This information is largely unavailable. Meanwhile, revelation of competition interaction would provide guidance for silvicultural operations, such as weed control, and selective thinning.

Models and Methods

Data used in this study were from the Coop thinning dataset. The stand summary statistics are listed in Table 5.1. The proportion of hardwood is fairly low, ranging from 0 - 19.4% of the total basal area at the plot establishment. Typically, hardwood presence is about 5%.

In order to simplify competition model specification and because of the limits of the dataset, trees were divided into two categories: (i) loblolly pine (*Pinus taeda L.*), and (ii) hardwoods, consisting of oaks (*Quercus spp.* L.), yellow poplar (*Liriodendron tulipifera* L.), hickories (*Cayva spp.* Nutt. (Hicoria Raf.)), maples (*Acer spp.* L.), sweetgum (*Liquidambar styraciflua* L.), blackgum (*Nyssa sylvatica.* L.) and others.

Although the previously discussed models appeared to be readily applicable in loblolly pine and hardwood mixed stands, careful examination revealed that those two categories of species were not evenly interspaced in the Coop thinning study plots. A simple density measure such as basal area was not sufficient to accurately quantify the presence of a species for a mixed stand. Thus, an individual tree basis was used to examine competition effects. The point density around one tree, instead of a whole stand density measure, can be assessed and used as a competition measure, equivalent to a neighborhood analysis. For each subject tree, competitors were chosen with a BAF of 10 ft^2 per acre using the point sampling method. This method of neighbor selection has been empirically demonstrated to result in higher correlation with tree growth (Daniels 1976). Any trees which may have competitors situated outside of the plot were excluded. Applying this criterion, 245 loblolly pine and 118 hardwood trees were obtained, from the Coop thinning study dataset, which had both loblolly pine and hardwood competitors. The basal area growth of individual tree was calculated for 3 year, 6 year and 9 year intervals. The following formula, a version of Hegyi type index (Hegyi 1974), was used to calculate the competition index:

Table 5.1. Summary statistics of loblolly pine of the thinning study at the plot establishment

Thin Regime	Age	Site Index	Before thinning		After thinning	
			$\overline{DBH}$	$\overline{BA}$	$\overline{DBH}$	$\overline{BA}$
		m	cm	m^2/ha.	cm	m^2/ha.
			Loblolly Pine			
Control	8-25	9.9-26.4	14.48	22.76		
Light Thin	8-25	9.6-26.4	14.48	25.21	16.00	18.55
Heavy Thin	8-25	9.1-26.6	14.48	25.16	16.51	15.17
			Hardwoods			
Control			9.00	0.48		
Light Thin			9.30	0.59	10.17	0.46
Heavy Thin			9.31	0.59	9.70	0.42

Note: Each treatment has 186 plots.

$$CI_s = \sum_{c}^{n} \frac{(DBH_c/DBH_s)^2}{DIST_{sc}}; \qquad [5.8]$$

Where:

CI_s	Competition index for subject tree s.
DBH_s	DBH of subject tree s.
DBH_c	DBH of competitor c.
$DIST_{sc}$	Distance between subject tree s and competitor c in meters;
n	Number of competitors.

For each subject tree, the neighboring loblolly pine competition index and the hardwood competition index were computed separately. The notation is summarized below:

CI_{pp}	Competition measure of competitor loblolly pine trees on a subject loblolly pine tree.
CI_{ph}	Competition measure of competitor loblolly pine trees on a subject hardwood tree.
CI_{hp}	Competition measure of competitor hardwood trees on a subject loblolly pine tree.
CI_{hh}	Competition measure of competitor hardwood trees on a subject hardwood tree.

Based on the considerations above, the basic models for basal area growth Y (cm^2) of species i were:

$$\log(Y_i) = \beta_{0i} - \beta_{ii}CI_{ii} - \beta_{ji}CI_{ji}; \qquad [5.9]$$

and

$$1/Y_i = \beta_{0i} + \beta_{ii}CI_{ii} + \beta_{ji}CI_{ji}. \qquad [5.10]$$

Since the logarithmic form fitted this dataset better than the reciprocal transformation (slightly higher R^2), the following discussion is based only on results using Equation [5.9].

The parameter estimates and fit statistics all have some biological interpretation. Intercept, β_{0i}, is amount of growth when trees are free of intertree competition; therefore, it can be considered as growth potential for species i. The impact of competition can be measured by the amount of growth loss due to neighborhood interference and thus can be inferred from the regression coefficients of β_{ii} and β_{ij}. Partial coefficients of correlation for each component of competition quantify impact of inter- and intra-specific competition respectively, while the coefficient of determination of full models may indicate importance of competition on tree growth relative to other factors such as site quality and climate conditions (Shainsky and Radosevich 1991).

It should be borne in mind that the explanation of β_{ii} and β_{ji}, and associated partial correlation coefficients, requires that the intra- and inter-specific competition measures be independent. Otherwise, any conclusions are dubious due to the multicollinearity. This requirement should also be met for a stable estimation of model parameters. Since our data are not from an orthogonally designed experiment, some statistical test of multicollinearity is warranted. Therefore, collinearity diagnostic analyses based on eigenvalues of the correlation matrix and tests for heterogeneity [3] were carried out wherever necessary.

The subject trees selected were from three thinning regimes: control/ no-thin, light thin, and heavy thin. It is probable that trees from different regimes may respond to competition differently due to different levels of overall competition. Partial F-tests were carried out to examine the necessity of splitting trees into sub-datasets according to their thinning regimes based on the basal area growth reaction toward competition over a six year interval with Equation [5.9] (Table 5.2). The results indicated that splitting was necessary both for hardwood and loblolly pine. The pooling of trees from the control and light thin regimes was statistically appropriate both for loblolly pine (p-value = 0.8534) and for hardwood (p-value = 0.5078). However, further pooling was not justified by

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[3] SAS/STAT User's Guide, Release 6.03 Edition, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513

Table 5.2. Partial F-tests examining dataset structures with Equation [5.9]

Sources	DF	SSE	MSE	Partial F(DF)	p-value
	Loblolly pine 6-year basal area increment				
Complete model[1]	228	62.7102	0.2750		
2 subset model[2]	231	62.8597	0.2721	0.261(3,228)	0.8534
Pooled model[3]	234	65.4831		3.21(3,231)	0.0238
	Hardwood 6-year basal area increment				
Complete model	103	33.0650	0.3210		
2 subset Model	106	33.8104		0.78(3, 103)	0.5078
Pooled Model	109	38.7026		5.11(3, 106)	0.0024

[1] Complete model: models were fitted separately to observations from each of the three thin regimes.

[2] 2 subset model: models were fitted to a dataset containing observations from the heavy thin regime, and to another consisting of rest of observations, respectively.

[3] Pooled model: One model was fitted to all observations regardless of the thin regimes.

the partial F-tests for loblolly pine (p-value = 0.0238) or for hardwood (p-value = 0.0024). Further statistical analyses were applied to these two groups of data separately.

Results and Analyses

Responses of loblolly pine

The modelling of loblolly pine basal area growth by Equation [5.9] was summarized in Tables 5.3 - 5.4. The heterogeneity tests suggested that the homogeneous variance assumption was reasonably sound. Testing for multicollinearity revealed that the largest condition number (square root of the ratio of the largest over the smallest of the correlation matrix eigenvalues) was only slightly larger than 5, which is very much smaller than 30, a rule of thumb threshold value suggested by Myers (1990). Therefore, multicollinearity should not be of a major concern with the interpretation of these results.

1. Under higher overall competition (control and light thin regimes)

More than half of the variation in basal area growth could be accounted for by competition level alone (Table 5.3). Basal area growth was negatively correlated with competitor presence of both loblolly pine and hardwood. In relative terms, inter-specific competition appeared to be more influential than intra-specific competition on inhibiting loblolly pine growth. Roughly speaking, hardwood was three times as effective as loblolly pine on reducing loblolly pine basal area growth for the first two growth intervals. However, this competitive edge diminished when the nine year interval growth was considered.

For each subject tree, mean inter-specific competition level (about 0.037) was only about one sixth of intra-specific competition level (about 0.2). However, the type II partial R^2 of regression models

Table 5.3. Results from regression analysis relating basal area growth of loblolly pine trees to inter- and intra-specific competition indices

Attributes	Control and Light Thin Regimes		
	3 yr.	6 yr.	9 yr.
n	161	156	145
$\hat{\beta}_{0p}$	4.1881	4.8557	5.5653
$\hat{\beta}_{hp}$	6.6944	7.6781	6.9835
$\hat{\beta}_{pp}$	2.2413	2.4775	4.5334
$\hat{\beta}_{hp} / \hat{\beta}_{pp}$	2.99	3.10	1.54
R^2	0.5154	0.5194	0.5820
Heteroscedasticity test p	0.8174	0.6242	0.1580
Condition Number	3.2775	3.2655	4.5005
Mean CI_{hp}	0.03883	0.03690	0.03588
Mean CI_{pp}	0.2150	0.2016	0.1873
	Heavy Thin Regime		
n	84	81	75
$\hat{\beta}_{0p}$	4.4363	5.0903	5.6114
$\hat{\beta}_{hp}$	3.9812	3.6922	3.6808
$\hat{\beta}_{pp}$	4.2954	3.9581	4.7983
$\hat{\beta}_{hp} / \hat{\beta}_{pp}$	0.93	0.93	0.77
R^2	0.2930	0.2760	0.3488
Heteroscadesticity test p	0.7922	0.6958	0.7543
Condition Number	5.0190	4.9246	4.8090
Mean CI_{hp}	0.03083	0.03092	0.03020
Mean CI_{pp}	0.1221	0.1208	0.1188

Note: The Model is specified in Equation [5.9], and the basal area is in cm^2.

Table 5.4. Partial correlation coefficient of loblolly pine basal area growth with inter- and intra-specific competition indices

Variables	Control and Light Thin Regimes		
	3 yr.	6 yr.	9 yr.
CI_{hp}	0.1610	0.1796	0.1787
CI_{pp}	0.3354	0.3534	0.4474
	Heavy Thin Regime		
CI_{hp}	0.0541	0.0508	0.0532
CI_{pp}	0.2238	0.2084	0.2840

(Table 5.4) for CI_{hp} was about half as large as that for CI_{pp}, which strongly implied that hardwood competition played a disproportionately large effect on loblolly pine growth in an established stand.

2. Under lower overall competition (heavy thin regime)

One obvious contrast between the plots involving control and light thin regimes and heavy thin regime was that consistently less variance of basal area growth could be explained by competition level under the heavy thin regime (around 30%) (Table 5.3). This indicated that intertree competition was much less severe. The second recognizable phenomenon was that $\hat{\beta}_{hp}$ was not much different from $\hat{\beta}_{pp}$, which suggested that hardwood had almost the same effect on loblolly pine growth as loblolly pine competitors.

Under a low level of competition, hardwood neighbors acted more or less as loblolly pine neighbors did. The partial R^2 for each kind of competition was proportional to the magnitude of their relative value. One possible reason may be that hardwood species lose their interference capability relative to loblolly pine when suddenly released because tolerant tree species are adapted to grow well under moderate degrees of shading. Hardwoods need time to acclimate to the new habitat, while this change of habitat is beneficial for growth of intolerant tree species like loblolly pine. Another explanation for this phenomenon may be that there are substantial differences about the relative size of loblolly pine and and hardwood trees among the thinning regimes. Therefore, the differences between the interference magnitude under different thinning regimes may be attributed to their different relative sizes. Data in Table 5.1 indicated that both loblolly pine and hardwood were increased in their average size after thinning. However, their relative size are almost invariant among the thinning regimes and between before and after thinning. Therefore, it is more plausible that the changed interference magnitude of hardwoods has more to do with changed stand environment.

Response of hardwood basal area growth.

The basal area growth of hardwood was fitted to intra- and inter-specific competition indices by Equation [5.9] as what was done for the loblolly pine. The regression results (Table 5.5 - 5.6) indicates that the homogeneity of variance assumption was not met in most cases. However, multicollinearity was not statistically significant, which is more crucial for stability of coefficient estimates.

1. Under higher overall competition (control and light thin regimes).

At a higher level of competition, intra-specific competition had a much greater effect on hardwood growth than inter-specific competition (Table 5.5). Approximately 42% of the variation in

Table 5.5. Results from regression analysis relating basal area growth of hardwood trees to inter- and intra-specific competition indices

	Control and Light Thin Regimes		
Attributes	3 yr.	6 yr.	9 yr.
n	68	61	54
$\hat{\beta}_{0h}$	2.9627	3.5503	3.8423
$\hat{\beta}_{hh}$	0.6648	0.9888	1.2683
$\hat{\beta}_{ph}$	0.3760	0.3295	0.2468^1
$\hat{\beta}_{hh} / \hat{\beta}_{ph}$	1.77	3.00	^{2}
R^2	0.3869	0.4553	0.3628
Heteroscedasticity test p	0.0662	0.0198	0.0009
Condition Number	3.5886	3.5417	3.5460
Mean CI_{hh}	0.2909	0.2884	0.3021
Mean CI_{ph}	1.0134	1.0366	1.0598
	Heavy Thin Regime		
n	50	52	42
$\hat{\beta}_{0h}$	3.6213	3.8596	4.7709
$\hat{\beta}_{hh}$	0.1616^1	0.0033^1	0.0926^1
$\hat{\beta}_{ph}$	1.5594	0.7944	1.8992
$\hat{\beta}_{hh} / \hat{\beta}_{ph}$	^{2}	^{2}	^{2}
R^2	0.4808	0.4653	0.5082
Heteroscedasticity test p	0.0242	0.0755	0.0044
Condition Number	4.7105	3.1978	4.7509
Mean CI_{hh}	0.3109	0.3348	0.3147
Mean CI_{ph}	0.4780	0.5548	0.4279

Note: The Model is specified in Equation [5.9], and the basal area is in cm^2.

[1] statistically not significant, i. e., p-value > 0.05.

[2] not applicable since one of the parameter estimates was not statistically significant.

hardwood basal area growth can be explained by neighborhood interference. Because of their small stature, hardwood trees typically were subject to a much higher competition level as compared to their loblolly pine neighbors. Considering the very low proportion of intra-specific competitors, it seemed that hardwood growth was strongly inhibited by other hardwoods (Table 5.6).

Another noticeable phenomenon was that hardwood species increased their intra-specific interference magnitude over time compared with the magnitude of interference which they received from loblolly pines. Hardwood interference capability over loblolly pine also diminished with an increased growth interval modelled under the control and light thin conditions (Table 5.3). There may be some niche differentiation between hardwoods and loblolly pines, similar to that reported between ground nuts and maize (Spitters 1983). Right after thinning, growth resource supply is relatively ample, especially light condition. Probably, loblolly pine growth is largely restricted by the soil nutrient and water supply, which may be usurped by hardwood species. It is also possible that loblolly pines allocated a large share of photosynthate to develop their crown instead of their diameter right after release. Therefore, hardwood showed a larger interference magnitude. However, with elapsed time after thinning, loblolly pines establish their dominance on light interception, hardwood species growth would be retarded by insufficient light supply. The relative advantage of hardwood over loblolly pine will diminish. As for hardwoods, with intensified competition, intra-specific competition becomes more prominent compared with inter-specific competition because niches of hardwoods, which are different from those of loblolly pine, are overlapped in the forest ecosystem. This hypothesis warrants more studies under controlled experimental conditions.

2. Under lower overall competition (heavy thin regime).

When stands were not very crowded, loblolly pine neighbors exercised a vital role in hardwood tree growth (Table 5.5). The β_{hh} estimates were extremely low and statistically insignificant. This phenomenon coincides with low $\hat{\beta}_{hp}/\hat{\beta}_{pp}$ under the heavy thin regime. It seems to suggest that

Table 5.6. Partial correlation coefficients of hardwood basal area growth with inter- and intra-specific competition indices

Variables	Control and Light thin Regimes 3 yr.	 6 yr.	 9 yr.
CI_{hh}	0.2116	0.2028	0.1347
CI_{ph}	0.0465	0.1149	0.0999
	Heavy Thin Regime		
CI_{hh}	0.0173	0.0008	0.0018
CI_{ph}	0.4806	0.4070	0.5065

intra-specific competition is insignificant in reducing hardwood basal area growth when the overall competition is below a threshold. Similar phenomena were observed by Simard (1990a and 1990b). Simard (1990a) found that there was no significantly negative, but occasionally positive relationships between lodgepole pine growth and Sitka alder cover when the alder cover was below 10%. Simard (1990b) also observed that Douglas fir did not respond further to birch density increase beyond a ecological competition threshold, which depended on site quality. It is possible that there may exist a threshold competition level for hardwood growth. It is also probable that changed light condition in heavily thinned plots resulted in less competitive response from hardwood species, which are not well adapted to the high light intensity (Spurr and Barnes 1980) in thinned plot and have to be acclimated to the new habitat. It is plausible that such a "thinning shock" would be more obvious in tolerant species than in intolerant species.

Significance of distinguishing inter- and intra-specific competition effects.

Another question under investigation is whether or not it is necessary to distinguish intra-specific competition from inter-specific competition. In other words, is a general competition index, which includes both kinds of competition, sufficient? If so, the modelling of competition effects would be simplified for stand growth simulators. The following model:

$$\log(Y_i) = \beta_{0i} - \beta_i CI \qquad [5.11]$$

was proposed and its behavior was compared with that of Equation [5.9] for both loblolly pine and for hardwood species. The partial F-tests for the two models were summarized in Table 5.7.

The responses towards separation of intra- and inter-specific competition indices were complicated. For loblolly pine, Equation [5.11] was just as good as Equation [5.9] under the heavy thin regime (p-value 0.9128), which agreed with the previous competitive edge comparisons. On the other hand, hardwood basal area growth was modelled about as well by combined competition indices, as by separated indices under the control and light thin regimes (p-value 0.1164). In the remaining two situations, separation of intra- and inter-specific competition significantly and substantially affected the modelling of tree basal area growth. Thus it can be concluded that separation of two kinds of competition measures helped to increase the accuracy of modelling tree basal area growth to a certain extent.

Because modelling with Equation [5.11] was not complicated by multicollinearity and also yielded better error structures, clearly indicated by the heteroscedasticity tests (Tables 5.8-5.9), interpretation of the modelling would provide simplified information about some biological characteristics of loblolly pine and hardwood related to intertree competition, such as growth potential and competition tolerance.

Table 5.7. Significance tests of differentiating inter- and intra-specific competition on modelling basal area growth over a six year interval

	Control and Light thin			Heavy thin		
species	DF	Partial F	p-value	DF	Partial F	p-value
Loblolly pine	1,153	13.16	0.0004	1,78	0.02	0.9128
Hardwood	1,58	2.54	0.1164	1,48	4.50	0.0391

Note: Equation [5.9] is compared with Equation [5.11], and the basal area is in cm^2.

Regression coefficients quantified responses of loblolly pine and hardwood basal area growth to different levels of competition (Tables 5.8 - 5.9). Theoretically, the values of β_{0p}, which expressed the potential growth, should be invariant among the thinning regimes for the same tree species. However, their estimates changed slightly (Tables 5.8 - 5.9), partially because the estimates of β_i by the ordinary least square method are always correlated with that of intercept (Myers 1990). Nevertheless, the growth potential of loblolly pines seemed to be higher than their hardwood counterpart. The slopes, suggesting competition tolerance, were also consistently lower under control and light thin, compared to those under heavy thin, which indicated that trees somehow adjusted themselves to the competition and became more competition tolerant under higher levels of competition. The same results were found with hardwood. The variable competition tolerance under different thinning regimes might be explained by the ecophysiological finding that trees changed their crown architecture, anatomy of photosynthetic organs, and even their physiology to accommodate to a certain stand environment (Spurr and Barnes 1980, Kramer and Kozlowski 1979). However, under any circumstance, hardwood trees exhibited a much flatter slope (lower β_i values) and a smaller intercept than pine trees (Figure 5.1), which might be controlled by the genetic makeup of each species. It has long been known that loblolly pine is generally less shade tolerant than the hardwood species included in the dataset analyzed here (Baker 1950).

Table 5.8. Results from regression analysis relating basal area growth of loblolly pine trees to overall competition indices

Attributes	3 yr.	6 yr.	9 yr.
	Control and Light Thin Regimes		
n	161	156	145
$\hat{\beta}_{0p}$	4.1268	4.7748	5.5658
$\hat{\beta}_p$	2.6807	2.9432	4.9293
R^2	0.4809	0.4781	0.5734
Heteroscedasticity test p	0.2868	0.2739	0.0470
Mean CI	0.2538	0.2385	0.2233
	Heavy Thin Regime		
n	84	81	75
$\hat{\beta}_{0p}$	4.4349	5.0892	5.6058
$\hat{\beta}_p$	4.2231	3.8963	4.5341
R^2	0.2930	0.2760	0.3465
Heteroscedasticity test p	0.1529	0.1517	0.6124
Mean CI	0.1529	0.1517	0.1490

Note: The model is specified in Equation [5.11], and the basal area is in cm^2.

Table 5.9. **Results from regression analysis relating basal area growth of hardwood trees to overall competition indices**

Attributes	3 yr.	6 yr.	9 yr.
	Control and Light Thin Regimes		
n	68	61	54
$\hat{\beta}_{0h}$	2.9328	3.4844	3.7223
$\hat{\beta}_{h}$	0.4175	0.4232	0.3853
R^2	0.3862	0.4314	0.3132
Heteroscedasticity test p	0.7908	0.7229	0.4869
Mean CI	1.3042	1.3250	1.3619
	Heavy Thin Regime		
n	50	51	42
$\hat{\beta}_{0h}$	3.6211	3.9350	4.7628
$\hat{\beta}_{h}$	1.0473	0.5814	1.1205
R^2	0.3295	0.4152	0.3207
Heteroscedasticity test p	0.2589	0.5669	0.4202
Mean CI	0.7889	0.8897	0.7426

Note: The model is specified in Equation [5.11], and the basal area is in cm^2.

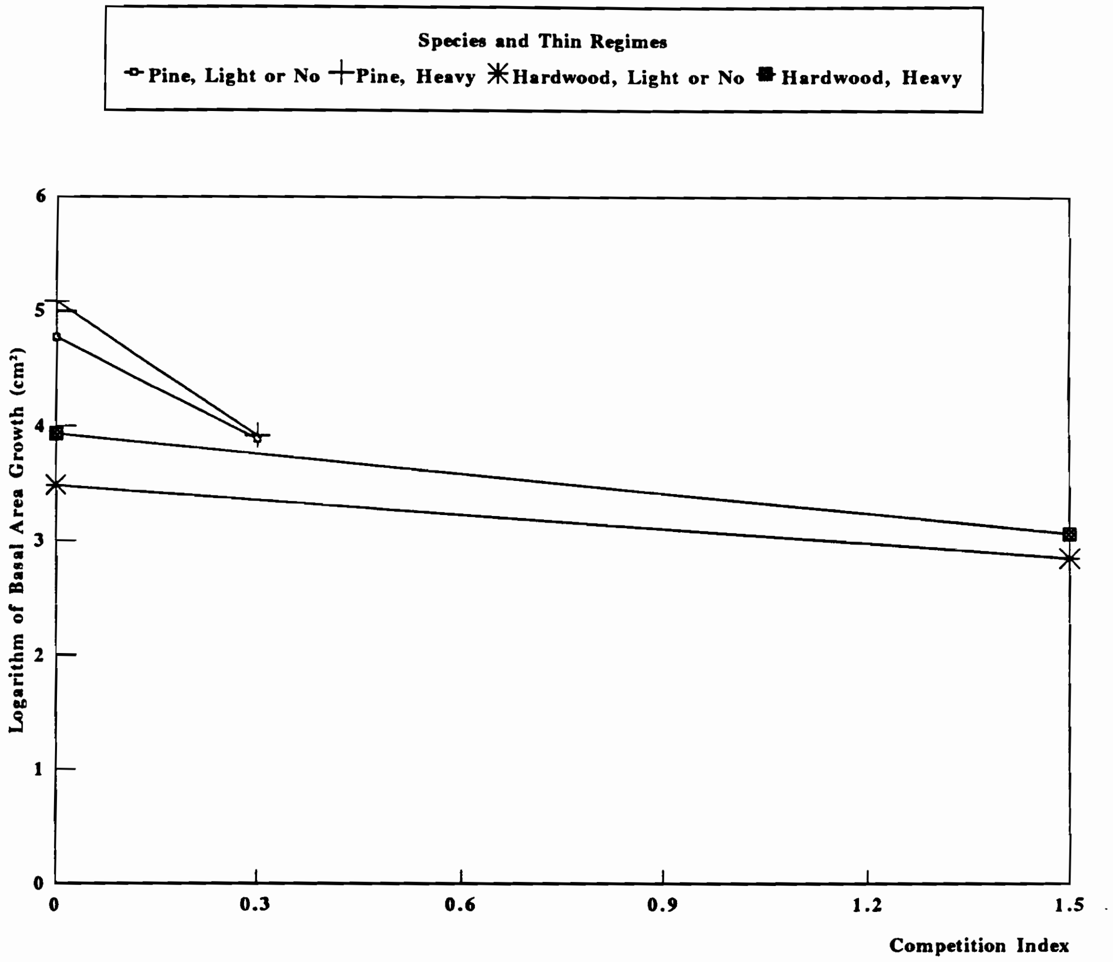

Figure 5.1. Basal area growth (cm^2) over a six year period under different thinning regimes.: Models are specified in Table 5.8 and Table 5.9.

Simulation Validation by PTAEDA2.

A forest stand simulator, PTAEDA2, was developed to model growth in loblolly pine plantations on cutover, site-prepared areas (Burkhart *et al.* 1987). The loblolly pine trees with hardwood competitors were inputted into this simulator and a six year interval simulation was carried out to indirectly validate the finding of this study. Three methods to compute the competition indices were tried. The first method accounted only for intra-specific competition. The second method computed the intra-specific and inter-specific competition indices separately and then the sum of the two indices was inputted into the simulator. The third method was basically the same as the second. However, the intra-specific competition index was deflated by 80%, and the inter-specific competition index was inflated by 240%, which was based on the previous finding that the competitive ability of hardwood was about three times as large as loblolly pines on loblolly pine growth under higher level of competition. The deflating of intra-specific competition index was accomplished to balance inflation effect of inter-specific index in order to have a similar competition index structure to that of the dataset used in building PTAEDA2. The statistics of residuals (the predicted – the observed) are listed in Table 5.10.

Accounting for inter-specific competition and making some adjustment helped to improve the accuracy of height prediction. The third method of accounting for competition effects, which relied on the finding of this study, yielded the most accurate prediction of height growth. However, the diameter prediction did not respond properly to the adjustment. The third method resulted in the largest bias, underpredicting diameter growth by 0.27 cm. From Table 5.9, one may conjecture that the overprediction of total height somehow compensated for the underprediction of DBH, which lead one to the reexamination of relationships between DBH and total height of loblolly pines growing with hardwood competition.

Table 5.10. Mean and standard deviation (in parentheses) of residuals (predicted - observed) for a six-year projection of PTAEDA2

Competition Index	Control and Light thin		Heavy thin	
	DBH (cm)	Total Height (m)	DBH (cm)	Total Height (m)
n	156		81	
CI_{pp}	0.2117(1.1104)	0.1583(1.1013)	-0.1329(1.2151)	0.0771(1.3619)
$CI_{pp} + CI_{hp}$	-0.0933(1.0818)	0.0685(1.0961)	-0.4526(1.1925)	-0.0009(1.3542)
$0.8CI_{pp} + 2.4CI_{hp}$	-0.2718(1.1061)	0.0118(1.1046)		

Loblolly pine trees have been found to develop vertical growth at the expense of DBH growth when facing hardwood competitors (Amateis and Burkhart 1987). Therefore, tree form would differ between loblolly pine trees with and without hardwood competitors. A random sample with the same size and same age range as the study dataset previously described was drawn from a tree population of the thinning study dataset with only intra-specific competitors. The tree form models:

$$\frac{TH}{DBH^2} = \beta_0 + \beta_1 CI_{pp} + \varepsilon \qquad [5.12]$$

and

$$\frac{TH}{DBH^2} = \beta_0 + \beta_1 CI_{pp} + \beta_2 CI_{hp} + \varepsilon \qquad [5.13]$$

were fitted to the respective datasets, and the result given in Table 5.11.

Both models performed satisfactorily with values of R^2 equal 0.6946 for trees without hardwood competitors and 0.6619 for trees with hardwood competitors. These results indicated that the form

Table 5.11. Parameter estimates and fit statistics of tree form models for loblolly trees with or without hardwood competitors

	Without hardwood competitors		With hardwood competitors	
Parameter	Estimate	Std. error	Estimate	Std. error
β_0	4.3552	0.2113	4.8022	0.2194
β_1	23.0713	0.9978	15.2162	0.9069
β_2			31.5094	4.0449
R^2	0.6946		0.6619	
$s_{y.x}$	2.0738		1.9708	

of trees was highly related to the levels of competition which they experienced. The relative magnitude of $\hat{\beta}_1$ over $\hat{\beta}_2$ of Equation [5.13] suggested that loblolly pine trees grow vertically at the expense of DBH growth when they are subject to the inter-specific competition in order to receive the sun light.

Another indication of tree form difference was that the average value of H/DBH^2 was 8.1191 for the loblolly tree data set without hardwood competitors, as opposed to an average value of 8.5476 for the data set with hardwood competitors, although the trees with hardwood competitors experienced a higher level of competition stress (CI_{pp} 0.1740, CI_{hp} 0.03486) on average than the trees without hardwood competitors (CI_{pp} 0.1631). Amateis and Burkhart (1987) found that loblolly pine trees grown in old-field plantations were more conical in shape than trees from cutover-site plantations, which in turn were more conical than natural-stand-grown trees. In our case, trees under hardwood competition lived in a habitat more like natural-grown-trees, and would therefore have a more parabolic shape than trees without hardwood competition. The PTAEDA2 models were basically built for the cutover-site loblolly pine plantations and would yield a diameter larger than the actual for a given total height if the tree were subject to hardwood competition. This may explain the discrepancy of effectiveness among competition measures for DBH and total height projections for trees with hardwood competitors.

Therefore, the validation by PTAEDA2 did suggest that inter-specific competition was more influential than intra-specific competition. If only intra-specific competition is accounted for, or if inter-specific competition is accounted for in the same way as intra-specific under the control and light thin regimes, overprediction of total height and DBH would follow. If diameter prediction functions of PTAEDA2 are properly adjusted, and if some distinctions about the two kinds of competition are well identified, the predictive power of stand simulator could be improved for mixed loblolly pine stands.

Conclusions

An important limitation to this study is that a significantly negative correlation coefficient between tree basal area growth and neighborhood competition indices does not necessarily quantify the competitive relationship. The hypotheses about inter- and intra-specific competition have to be tested under controlled experimental conditions. Another limitation is that proportion of hardwood presence is rather low. The conclusions drawn from this study should be applied in the largely pine dominated plantations. However, trees selected in this study generally have neighborhoods with larger hardwood presence of about 10-45% on the basis of competition indices. Nonetheless, this research proposed a model for studying competitive relationships for survey data and the following conclusions may be reached:

1. Trees react to competition differently under different thinning regimes. Under high level competition, hardwood species exerted larger interference influences on reducing basal area growth, both intra- and inter-specifically, although they belong to sub-dominant or intermediate crown classes. However, under low-level competition, intra- and inter-specific competition were almost identical quantitatively in the impact on loblolly pine basal area growth. This result was indirectly validated with simulations using stand simulator PTAEDA2. Intra-specific competition was more effective in reducing hardwood basal area growth than inter-specific competition under high levels of competition. The basal area growth of hardwoods was significantly associated with levels of inter-specific competition, but not with intra-specific effects under a low level of competition. There may exist niche differentiation between hardwoods and loblolly pines. Some ecological competition thresholds are also probable with regard to the responses of tree species towards competition. These hypotheses need to be substantiated under controlled studies.
2. The Hegyi type competition indices could account for more than half of the variability in loblolly pine basal area growth under high levels of competition. However, only one third of

variability could be explained by the same model for loblolly pines under lower levels of competition. For hardwood species, the percentage of growth accounted for by the measure of competition was about 45% and did not change much among control, light thin, and heavy thin regimes.

3. Under higher levels of competition, trees managed to increase their competition tolerance (Spurr and Barnes 1980), which was reflected in lower β_i values (slope) in Equation [5.11], regardless of whether they were loblolly pine or hardwood trees. In this study, the growth potential of hardwoods were lower than those of loblolly pines.
4. Under the plantation situations studied, where hardwood presence is relatively scarce, hardwood species were always more tolerant to competition than loblolly pines, as indicated by lower growth potential (β_{0h}), and higher competition tolerance (β_h).
5. Separation of intra- and inter-specific competition and incorporation of both in growth models helped to improve the prediction of loblolly pine growth under higher competition levels and the prediction of hardwood species growth under lower levels of competition. In the other two cases, the effect of separation was not statistically significant.
6. The tree form of loblolly pine was significantly related to the levels of competition which it experienced. Under high level of competition trees grew vertically at the expense of horizontal growth. Hardwood competition had a more dramatic effect on loblolly pine tree form than intra-specific competition. However, it is possible to use the available stand simulators like PTAEDA2 for mixed stands projections if some adjustment in competition index computation and tree form relationships is made.

Practically speaking, this study indicated that if environmentally allowed and economically feasible, practices on controlling hardwood species, including releasing and selective thinning operation, would be more effective than thinning loblolly pine trees in order to maximize the yield of pine component.

Chapter 6. Spatial Autocorrelation Dynamics of Diameter and Total Height and Their Relations to Intertree Competition in Juvenile Loblolly Pine (*Pinus taeda* L.) Plantations.

Introduction

Most standard statistical analyses, including regression, variance analysis, and nonparametric methods, require independent observations for certain properties of parameter estimates. In most cases, we assume that observations are independent and proceed with a variety of statistical analyses without carefully examining this assumption. However, in forestry data, there are at least three sources which will generate dependent observations: remeasurement on experimental units (the temporal correlation), spatially positive correlation (caused by environmental heterogeneity or by contiguous pathogens or pest damage) and spatially negative correlation (incurred by competition).

The spatially interdependent variable X_i may be expressed by the following structure (Cliff and Ord 1981):

$$X_i = \rho \sum_j \omega_{ij} X_j + \varepsilon_i ; \qquad i = 1,\ 2,\ \ldots,\ n. \qquad [6.1]$$

$\{\varepsilon_i\}$ are independent and identically distributed variates with common variance, σ^2. The set of weights, $\{\omega_{ij}\}$, are any set of constants that specify which competitors in the study area are spatially related with X_i. The constant, ρ, is a measure of the overall level of spatial autocorrelation among the $\{X_i, X_j\}$ pairs for which $\omega_{ij} > 0$. Just as in the time series analysis, a dependent observation carries less information than an independent observation in the usual situation of spatial autocorrelation, since it is partly predictable from its neighbors. The presence of autocorrelation among the population error terms of the dependent variables leads to biased estimates of the residual variance and less precise estimates of the regression parameters when the method of ordinary least squares (OLS) is applied (Cliff and Ord 1981).

Procedures developed in geological sciences and statistics allow one to cope with this problem. One way is trend surface analysis (Davis 1986, Onwin 1975), by which an observation on a spatially distributed variable is divided into a component associated with any regional trends present in the data and a component associated with purely local effects. This separation into components is accomplished by fitting a best-fit response surface of a previously specified type using standard regression techniques (Davis 1986, Onwin 1975). The predicted trend values can be designated regional effects, whereas the local departures of observed data from it, or residuals, are considered to be local effects. The trend surface analysis has been found useful in descriptions of systematic variation of soil properties and in reserve explorations (Davis 1986). Other methods, like Moran's index, and the Geary index (Ebdon 1985) could also be used to diagnose spatial autocorrelation. Furthermore, a different approach may be taken by specifying an autocorrelated structure for the error terms and by choosing appropriate estimation procedures, which might lead to an unbiased estimate of σ^2 and efficient estimates of the regression coefficients (Cliff and Ord 1981, Gregoire 1987).

Various approaches to these problems have been suggested (Reed and Burkhart 1985, Gregoire 1985, 1987, Magussen 1989). When developing a yield equation for Douglas-fir, Gregoire (1987) recognized the nature of remeasurement data from permanent forest plots to be temporally and spatially correlated. He differentiated the error term of his yield equation into three sub-categories, i. e. temporal effect, plot (spatial) effect and residual random effect. Each of these possessed distinct variance and covariance structures. Four error structures were specified. They were: (1) uncorrelated and homoscedastic plot and time effects; (2) autoregressive time effects; (3) uncorrelated and heteroscedastic plot effects, autoregressive time effects and (4) correlated and heteroscedastic plot effects, autoregressive time effects. His results showed that ordinary least squares nearly always had the least prediction error, whereas one or more of the alternate specifications produced higher likelihood.

Apart from the problems caused by autocorrelation, spatial patterns themselves are a very informative area for an ecologist. Various techniques and procedures had been developed in the field of spatial statistics (Diggle 1976 and 1983, Odland 1988, Ebdon 1985, Getis and Boots 1978, Ripley 1981) and a few applications have appeared in publications of many branches of biology (Sokal and Oden 1978a, 1978b, Reed and Burkhart 1985, Ford and Diggle 1981, Renshaw 1984, Biging and Dobbertin 1989, and Cormack and Ord 1979). The emphasis lies in the diagnosis and analysis of autocorrelation, which are equivalent to examining whether the observed value of a nominal, ratio, ordinal or interval variable at one locality is independent of the value of the variable at neighboring localities. The indices like Moran's or Geary's (Ebdon 1985) were advanced for various data types and were proved to be asympototically normally distributed as sample number increased. The latter property facilitates a common normal mean test, in addition to the randomization test. Sokal and Oden (1978a, 1978b) cited examples of autocorrelation test applications in genotype of individual mice, blood group frequencies in humans, gene frequency variation in a perennial herb, and the distribution of species of trees. Reed and Burkhart (1985) failed to find significant spatial autocorrelation associated with variables like tree defects and basal area, but they detected a significant autocorrelation of species classification. Nonetheless, for individual tree basal area, they found that the levels of spatial autocorrelation tended to be positive for low levels of competition, negative at intermediate levels of competition and positive again at high levels of competition. This research indicated that the confounding of competition effects and microsite variation made the autocorrelation test less powerful because the positive and negative autocorrelations tend to cancel each other.

For some complex spatial patterns from the natural environment, spectral analysis may act as a discerning and interpreting tool (Cliff and Ord 1981, Bartlett 1975, Jenkins and Watts 1968, Fisher 1973, Jumars *et al.* 1977). For example, Bartlett (1975) calculated the two dimensional spectra of two stands of Japanese black pine saplings and inferred an inhibition process between plants. McBratney and Webster (1981) analyzed the yields of wheat grain and straw obtained by Mercer and Hall (1911), and showed periodic effects attributed to an earlier ridge and furrow system (Renshaw and Ford 1983). Ford (1976) used spectral analysis to describe a canopy surface of complex roughness. By constructing a two-dimensional power spectrum of canopy surface of a Scots pine stand, the relationship between surface structure and wind flow patterns was recognized, which was not apparent when measurements on individual trees were considered alone. The application of spectral analysis is limited to a larger extent by the requirement of a large sample.

Spatial statistics not only help to understand the spatial patterns of stand characteristics, but also have some practical applicability. The autocorrelation information can be used to assign tree dimension in an individual tree based stand growth simulator as Reed and Burkhart (1985) pointed out. The spatial pattern is also an indication of competition, and/or systematic environmental variations, which one needs to be aware of and to address properly with appropriate statistical techniques. Research involving data on spatial characteristics of juvenile loblolly pine plantation data would reveal some biological information, and at the same time provide guidance for model building.

Methodology

Trend surface analysis.

The most difficult aspect of trend surface analysis is without doubt trend specification. Underspecification would definitely not be able to separate the systematic variation from the local effect, in our case competition effect. However, it is equally, if not more, important for us not to overspecify the trend surface models. Otherwise, some local effect could be confounded with the systematic effect so that one may wind up dealing with artifacts when doing residual analysis. If the danger is to be avoided, a trend surface model should be as simple as possible. Therefore, a second order trend surface was employed in this study, which took the form:

$$Y_{ijt} = \beta_{0t} + \beta_{1t} I + \beta_{2t} I^2 + \beta_{3t} J + \beta_{4t} J^2 + \beta_{5t} I \times J + \varepsilon_{ijt.} \qquad [6.2]$$

Where;

y_{ijt}	Observations on diameter, or total height of tree in row i and column j at t^{th} measurement.
I	Row number.
J	Column number.
$\beta_{0t} - \beta_{5t}$	Parameters to be estimated.
ε_{ijt}	Residuals of trend surface model, which could be considered as competition effects and will be tested for autocorrelation.

Autocorrelation tests.

The Moran and Geary indices are used most often in measuring and testing spatial autocorrelation. The Moran index is defined as:

$$I = \frac{n \sum_i \sum_j w_{ij}(z_i z_j)}{2A \sum_i z_i^2} . \qquad [6.3]$$

Another index is given by Geary:

$$C = \frac{(n-1) \sum_i \sum_j w_{ij}(x_i - x_j)^2}{4A \sum_i z_i^2} . \qquad [6.4]$$

Where;

W	$\equiv \{w_{ij}\}$. A generalized weighting matrix, denoting effects of subject i on subject j. In this study, w_{ij} is defined to be binary. When x_i not being associated with x_j, $w_{ij} = 0$ When x_i and x_j being associated, $w_{ij} = 1$.
x_i	Residuals of observations from trend surface analysis.
z_i	Is equal to $x_i - \bar{x}$. Because $\bar{x}$ mean of the spatial variable X, is zero, z_i is identical to x_i
n	The number of individuals in a population.
L_i	The number of individuals joined with the i^{th} individual.
A	Is equal to $\frac{1}{2} \sum_i \sum_j w_{ij}$ The total number of joints.

Both Moran's I and Geary's C are asympototically normally distributed under the assumption of no spatial autocorrelation (Griffith 1987, Cliff and Ord 1981). The moments of I and C can be derived under either of two assumptions, normality or randomization. The former assumes that x_i is from a Gaussian distribution. And the latter considers the observed I or C values from a pool of all possible values if the x_i's are randomly permuted spatially, regardless of the underlying distribution of X.

The expectation and variance of Moran's I (Cliff and Ord 1981, Reed and Burkhart 1985) is:

Under the normality assumption

$$E(I) = -\frac{1}{n-1} \qquad [6.5]$$

$$V(I) = \frac{4An^2 - 8(A+D)n + 12A^2}{4A^2(n^2-1)} - \frac{1}{(n-1)^2}. \qquad [6.6]$$

Under the randomization assumption

$$E(I) = -\frac{1}{n-1}. \qquad [6.7]$$

$$V(I) = \frac{1}{4A^2(n-1)(n-2)(n-3)}[n(4A(n^2-3n+3) - 8(A+D)n + 12A^2) + b_2(4A(n^2-n) - 16(A+D)n + 24A^2)] - \frac{1}{(n-1)^2} \qquad [6.8]$$

The expectation and variance of Geary's C (Cliff and Ord 1981, Reed and Burkhart 1985) is:

Under the normality assumption

$$E(C) = 1.$$

$$V(C) = \frac{(2A+D)(n-1) - 2A^2}{(n+1)A^2}. \qquad [6.9]$$

Under the randomization assumption

$$E(C) = 1.$$

$$\begin{aligned} V(C) = {} & \frac{1}{n(n-2)(n-3)2A^2}\{2A^2[-(n-1)^2 b_2 + (n^2-3)] \\ & + 2A(n-1)[-(n-1)b_2 + n^2 - 3n + 3] \\ & + (D+A)(n-1)[(n^2-n+2)b_2 - (n^2+3n-6)]\} \end{aligned} \qquad [6.10]$$

Notation for Equations 6.5-6.10;

n	The number of individuals in a population.
L_i	The number of individuals joined with the i^{th} individual.
A	Is equal to $\frac{1}{2}\sum_i L_i$ The total number of joints.
D	Is equal to $\frac{1}{2}\sum_i L_i(L_i - 1)$.
b_2	Is equal to m_4/m_2^2. m_j is the i^{th} sample central moment.

Others were defined as in Equation 6.3-6.4.

Specification of the weighting matrix is a subtle task and subject to some 'prior' considerations and data limits. Because the main purpose of this study was to determine the relationships between intertree competition and spatial characteristics, and because individual trees were situated in well designed grid positions, only trees in the same column were associated in tree pairs, *i. e.,* $w_{ij} = 1$, otherwise, $w_{ij} = 0$. The preliminary analysis indicated that associating trees in the same rows also yielded similar outcomes as associating tree in the same column. However, without intentionally separating row and column effects, spatial patterns became too complicated to have meaningful results. The pairs of first degree were defined to be trees next to each other. The pairs of second degree were a pair of trees with another tree between them. The pairs of third degree were trees with two trees between them, *etc.* In this manner, the effects of row can be easily separated from the effects of column.

The residuals of trend surface equations, which are supposed to reflect the local effects, were used to compute the Moran's I and Geary's C on tree diameters and total height. Each spacing treatment included three replications at four locations for the first seventh measurements and three replications at three locations for the eighth year remeasurement. The corresponding significance tests were carried out for both Moran's I and Geary's C.

Moran and Geary indices are inversely related (Griffth 1987). Structurally, the Geary index is more sensitive to data pairs with larger differences, whereas the Moran index is more stable. In our study, the Moran index resulted in more consistent tests over time. The estimates of variance of Geary's C are not guaranteed to be estimable, and sometimes are extremely small under the randomization assumption as opposed to estimates under the normality assumption with our dataset. Cliff and Ord (1981) also found that the efficiency of Moran's I was generally a little better than that of Geary's C. The significance tests with Moran's I were slightly more conservative under randomization than those under normality, but were nonetheless dynamically very similar. Thus, only Moran index tests under normality were presented for the sake of brevity.

Mathematical modelling of spatial pattern.

If negative autocorrelation could be detected, it might be described by some oscillatory relationship like trigonometric functions. One possibility was the two dimensional Fourier model, which was given by:

$$\begin{aligned} Z_{IJt} &= \beta_{0t} + \beta_{1t}\cos(\pi I)\cos(\pi J) + \beta_{2t}\cos(\pi I)\sin(\pi J) \\ &\quad + \beta_{3t}\sin(\pi I)\cos(\pi J) + \beta_{4t}\sin(\pi I)\sin(\pi J) \end{aligned} \qquad [6.11]$$

Where;

z_{ijt}	Local effects (residuals) from trend surface functions of the tree in row i and column i at $_{t}th$ remeasurement, which can be a diameter measures or a total height measures.
I, J	Row and column number for each tree.
β_{it}	Parameters to be estimated.

This form of Fourier model has been found to be suitable for some kinds of response surface and looks intuitively appealing. Therefore, it was utilized to model the competition induced spatial patterns for each spacing treatment.

Results and Analyses

Spatial Characteristics of Diameter Measurement

Spatially systematic variations of diameter measurements

The observations of diameter measurement were fitted to Equation [6.2] separately for each plot and each remeasurement. Since only 49 trees were planted in each plot, and some subsequent mortality further decreased number of observations for later remeasurements, and since there were five parameters to be estimated for a second order trend surface model, the power of significance tests was rather low. Therefore, $\alpha = 0.10$ was chosen to test the significance of trend surface. The number of plots which proved to have a significant microsite variation were summarized in Table 6.1 and plotted in Figure 6.1.

The percentage of plots with significant test results was surprisingly high (about 40%), especially at the very early stages of stand development. This percentage decreased very rapidly, from 40.1% at first measurement to 21.53% at eighth measurement, which may be explained by the fact that small seedlings were more sensitive to environmental influences. Juvenile trees do not have extensive root systems, and functionally are very localized. Therefore, even a small environmental gradient, such as a variable underground water level, would influence their growth enough so that a response surface could be statistically significant. Nevertheless, with a large capacity to exploit their growth resources, bigger trees would not appear to have positively correlated spatial patterns if the microsite variation is not large. Yet, one should realize that certain environmental conditions, such as a hardpan at a certain depth in the soil profile, which would not hinder tree growth until the root system reached to that depth, would cause trees to show positive autocorrelation in the later years of stand development. Among the plots studied, six plots, which did not exhibit significant spatial

Table 6.1. Numbers of plots with significant trend surface (p-value < 0.10)

Variable	Number of Plots		Percent significant
	Total	Significant	
D_1	192	77	40.10
D_2	192	88	45.83
D_3	192	76	39.58
D_4	192	72	37.50
D_5	192	72	37.50
DBH_5	192	71	36.98
DBH_6	192	65	33.85
DBH_7	192	48	25.00
DBH_8	144	31	21.53

[1] Where, D_1 is the ground line diameter at the first measurement,

D_2 is the ground line diameter at the second measurement, etc;

DBH_5 is the diameter at breast height at the fifth measurement, etc.

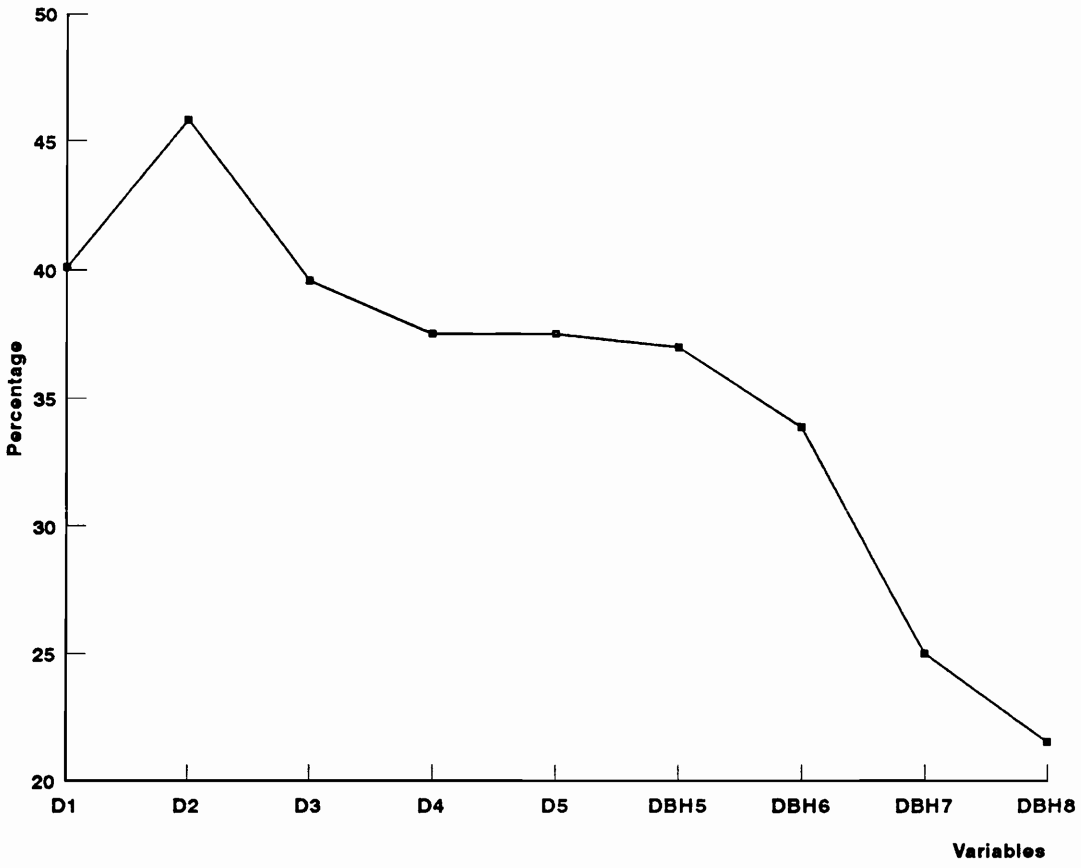

Figure 6.1. Percentage of plots with significant trend surface (p-value < 0.10) for diameter measurements.: Total plot number: 192 for first seven measurements, 168 for the eighth remeasurement.

patterns for diameter measurements during first five years, showed consistently significant positive spatial patterns on DBH in the sixth, seventh and eighth years. These plots might have some environmental factor which affected tree growth at later stages of stand development.

The effects of systematic environmental variation on error estimates of field experiments, such as randomized block designs, is a more serious problem than experimenters used to think (Bartlett 1978). If each tree observation were treated as an experimental unit as in cases where individual tree models are developed, positive trend surfaces would impose the same problem as in most agricultural trials. The value of each tree in a two-dimensional layout has to be adjusted by covariance with neighbouring trees somehow.

Autocorrelation indices and their corresponding significance tests on detrended diameter measurements

The Moran indices and their corresponding significance tests under the normality assumption were carried out, and the results were given in Table 6.2 and Table 6.3 for the pairs of first degree.

At first glance, it seemed that most Moran indices were negative. They ranged from 0.0059 to -0.2459. During the early stages of stand development, especially in the most most widely spaced treatments (for examples, 8 * 8 and 12 * 12 ft.), some very significant negative indices occurred, which might be caused by random errors, or by overspecification of trend surface models. As stands aged, Moran indices decreased to fairly large negative values. If generally ±1 can be considered as the range for Moran index, it could be inferred from Table 6.2 that competition processes were generating negative autocorrelation patterns on tree DBH.

It was interesting to notice that there was something peculiar about the Moran indices in spacing treatment 4 * 4 and 4 * 6 ft. for last two year observations. The reversion of signs from negative

Table 6.2. Moran indices of detrended diameter measurements

	Diameter measurement[1]								
Spacing (ft.)	D_1	D_2	D_3	D_4	D_5	DBH_5	DBH_6	DBH_7	DBH_8
4 * 4	0.0153	-0.0297	-0.0601	-0.1181	-0.1146	-0.1286	-0.1320	-0.1447	0.0018
4 * 6	-0.0408	-0.0714	-0.1535	-0.1732	-0.2063	-0.1955	-0.2166	-0.2459	-0.1927
4 * 8	0.0068	0.0098	-0.0013	-0.0371	-0.0392	-0.0406	-0.0703	-0.0992	-0.1235
4 * 12	0.0222	0.0192	0.0257	-0.0352	-0.0525	-0.0026	-0.0415	-0.0689	-0.1119
6 * 4	-0.0291	-0.0808	-0.0770	-0.0935	-0.1079	-0.0816	-0.1084	-0.1023	-0.1043
6 * 6	-0.0242	0.0195	-0.0870	-0.0942	-0.0798	-0.0544	-0.0814	-0.0968	-0.1274
6 * 8	-0.0093	-0.0275	-0.0103	-0.0396	-0.0221	-0.0793	-0.1213	-0.0912	-0.1350
6 * 12	0.0142	0.0039	0.0206	0.0016	-0.0149	-0.0027	-0.0224	-0.0125	-0.0443
8 * 4	-0.0388	-0.0227	-0.1107	-0.0584	-0.0840	-0.0612	-0.0994	-0.1101	-0.0901
8 * 6	0.0170	0.0025	-0.0099	-0.0227	-0.0137	-0.0359	-0.1079	-0.1200	-0.1100
8 * 8	-0.0784	-0.1220	-0.0770	-0.1086	-0.0955	-0.1168	-0.1411	-0.0853	-0.1283
8 * 12	0.0900	0.0505	0.0259	0.0077	0.0059	0.0440	0.0315	0.0157	-0.0047
12 * 4	0.0323	-0.0334	-0.0442	-0.0937	-0.0984	-0.1037	-0.1289	-0.1508	-0.1569
12 * 6	-0.0022	0.0307	0.0220	-0.0022	-0.0296	-0.0691	-0.0347	-0.0342	-0.0044
12 * 8	-0.0186	0.0214	0.0604	0.0250	0.0164	-0.0385	-0.0208	-0.0622	-0.0943
12 * 12	-0.0117	-0.0662	-0.0148	-0.0116	-0.0193	0.0124	0.0079	0.0198	0.0290

[1] Defined in Table 6.1.

Table 6.3. Moran indices Z of detrended diameter measurements under the normality assumption

	Diameter measurement[1]								
Spacing (ft.)	D_1	D_2	D_3	D_4	D_5	DBH_5	DBH_6	DBH_7	DBH_8
4 * 4	0.3813	-0.6224	-1.2972	-2.5823	-2.4910	-2.7770	-2.8584	-3.1313	0.0779
4 * 6	-0.8782	-1.5408	-3.3399	-3.7739	-4.4884	-4.2394	-4.7158	-5.3471	-3.6306
4 * 8	0.1923	0.2552	-0.0047	-0.7827	-0.8261	-0.8470	-1.5095	-2.1461	-2.1073
4 * 12	0.5378	0.4598	0.6028	-0.7290	-1.1044	-0.0186	-0.8633	-1.4526	-2.1044
6 * 4	-0.6160	-1.7646	-1.6723	-2.0400	-2.5336	-1.7622	-2.3549	-2.2084	-1.9394
6 * 6	-0.5068	0.4696	-1.8788	-2.0320	-1.7155	-1.1520	-1.7316	-2.0773	-2.3671
6 * 8	-0.1693	-0.5701	-0.1888	-0.8384	-0.4507	-1.7128	-2.6451	-1.9714	-2.5087
6 * 12	0.3568	0.1241	0.4908	0.0732	-0.2879	-0.0204	-0.4513	-0.2349	-0.8049
8 * 4	-0.8161	-0.4703	-2.4265	-1.2584	-1.8134	-1.2939	-2.1382	-2.3844	-1.6762
8 * 6	0.4212	0.0937	-0.1751	-0.4484	-0.2564	-0.7253	-2.2737	-2.5323	-2.0350
8 * 8	-1.7447	-2.6891	-1.6910	-2.3758	-2.0743	-3.1942	-3.0718	-1.8492	-2.4253
8 * 12	2.0627	1.1642	0.6132	0.2075	0.1680	1.0038	0.7276	0.3822	-0.0454
12 * 4	0.7645	-0.7024	-0.9377	-2.0269	-2.1192	-2.2206	-2.7747	-3.2456	-2.9358
12 * 6	-0.4579	0.7165	0.5211	-0.0083	-0.6021	-1.4446	-0.7084	-0.6978	-0.0395
12 * 8	-0.3796	0.5197	1.3882	0.5964	0.4045	-0.8171	-0.4249	-1.3389	-1.7733
12 * 12	-2.5814	-1.4284	-0.2891	-0.2159	-0.3869	0.3108	0.2115	0.4729	0.5974

Note: $p = 0.10$ for $Z = -1.645$.
$p = 0.05$ for $Z = -2.000$.
$p = 0.1$ for $Z = -2.58$.

[1] Defined in Table 6.1.

to positive, or decline of absolute Moran index values was different from the general trends of autocorrelation dynamics. It may be hypothesized that mortality, being occurred first in the highest density plots, made the adjacent trees have less negative or even positive autocorrelation.

Since tree pairs were formed only in the same column, it can be assumed that any dynamics differences of spatial autocorrelation characteristics were attributable to within-column distance, an indirect measure of intertree competition when between-column distance was fixed. Similarly, when within-column distance was fixed, other sources of variations could be identified.

Effects of Intertree competition on the autocorrelation indices: With controlled between-column distance, the Moran indices were plotted for various within-column distances in order to examine the effect of intertree distance on the autocorrelation (Figs. 6.2 - 6.5). Except for spacing treatments with between-column distance of 12 ft., the absolute values of Z of significance tests on Moran indices increased with tree growth.

At between-column distance of four feet (Fig. 6.2), significant autocorrelation can be found after the fourth remeasurement for spacing treatments 4 * 4, and 4 * 6 ft. Negative autocorrelation could be detected at the seventh remeasurement for treatment 4 * 8 ft., and at the eighth remeasurement for treatment 4 * 12 ft. Autocorrelation was more significant with the 4 * 6 than with the 4 * 4 ft. treatments after the seventh year. This may suggest that severe competition resulted in retarded growth for both subject and competitor trees, which would result in low absolute values of Moran index.

At a between-column distance of six feet, the same trend can be found as at the between-column distance of four feet. However, significant negative autocorrelation appeared approximately 1 year later respectively (Fig. 6.3).

There was something unusual with spacing treatment 8 * 8 ft., which showed very significantly negative autocorrelation all the time (Fig. 6.4), and was probably due to overspecification of trend

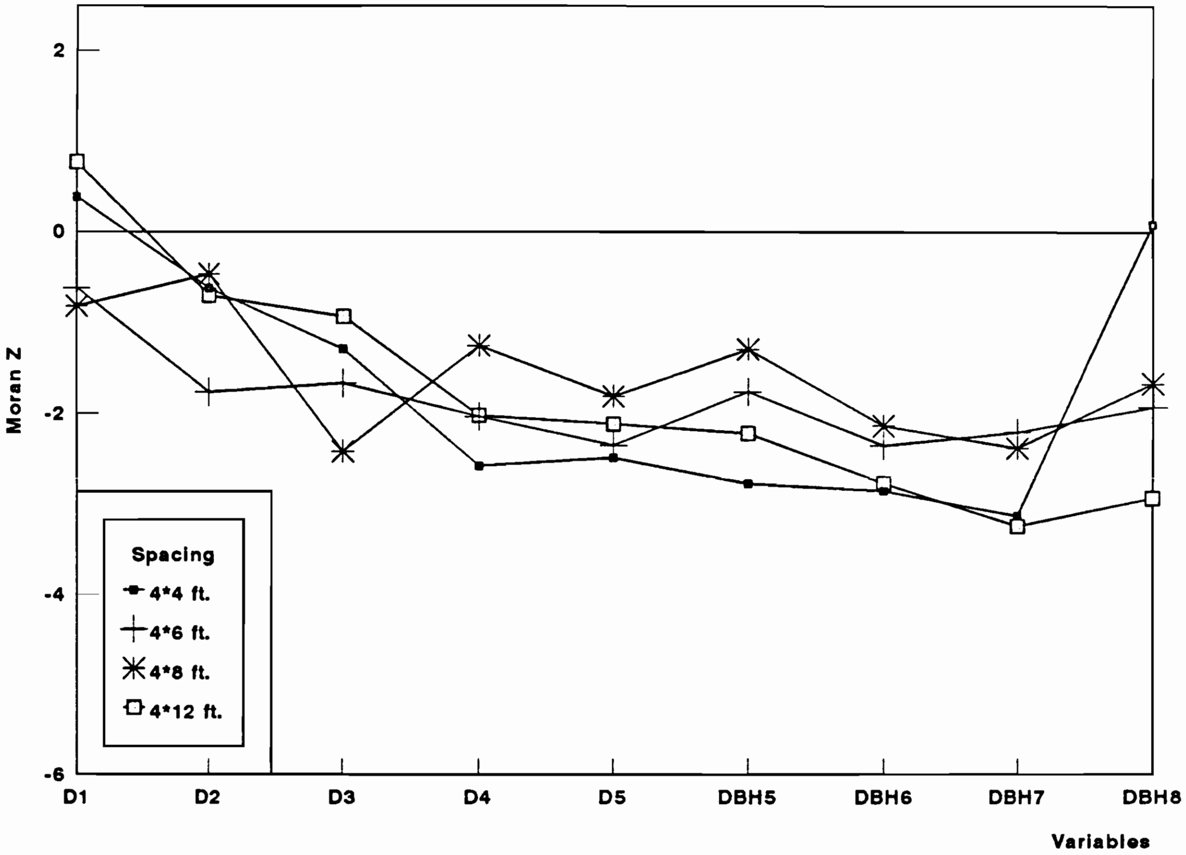

Figure 6.2. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: between-column distances fixed as four feet.

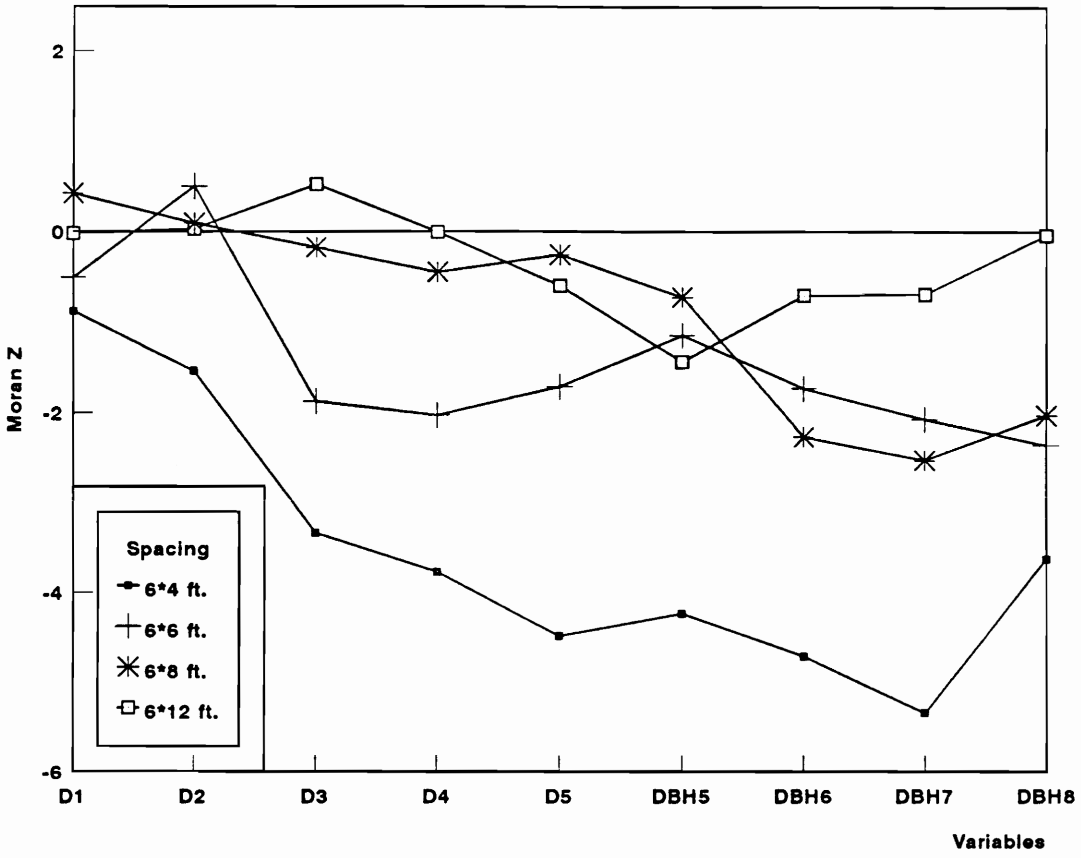

Figure 6.3. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: between-column distances fixed as six feet.

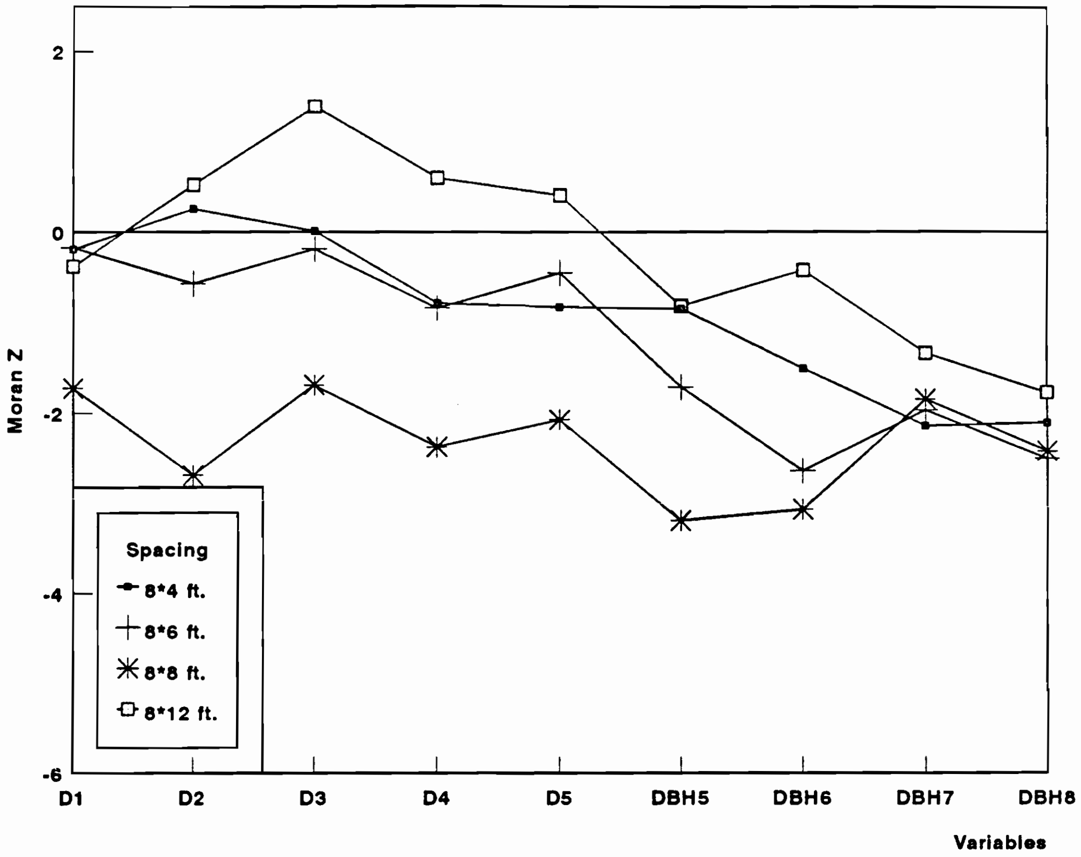

Figure 6.4. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: between-column distances fixed as eight feet.

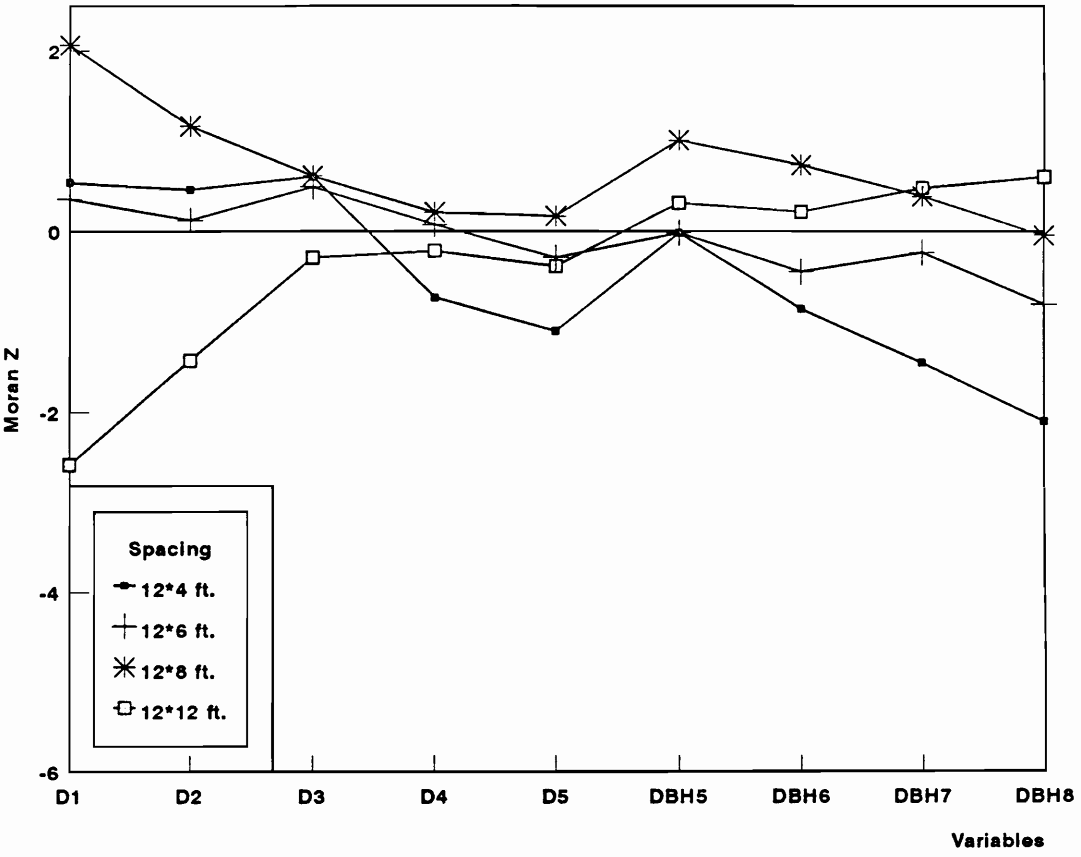

Figure 6.5. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: between-column distances fixed as twelve feet.

surface analysis, or due to very irregular microsite variation. For spacing treatments 8 * 4, and 8 * 6 ft., negative autocorrelation was very significant from the sixth remeasurement on. With a between column distance of twelve feet, significant autocorrelation could only be found when within-column distance was four feet after the fourth remeasurement (Fig. 6.5). Other plots showed fluctuated but insignificant Moran index dynamics, which implied that trees somehow avoided direct competition wherever there was room for crown and/or root system development as in spacings 6 * 12 and 8 * 12 ft.

Generally speaking, when between-column distances were fixed, the autocorrelation tests became more significant as the distances between tree pairs decreased. Therefore, it may be inferred that intertree competition was a significant factor generating the negative autocorrelation (Fig. 6.2 - 6.5). As trees grow, intertree competition materializes, negative autocorrelation patterns follow.

Autocorrelation index variation with fixed within-column distances.: With a fixed distance for trees associated for the computation of Moran's indices, the extent of autocorrelation varied when trees of interest had neighbors at different spacings (Figs. 6.6 - 6.9).

When the within-column distance was four feet, stands tended to have a significant negative correlation no matter how large between-column distances were. Here, tree pair distance was the principal factor, whose effects were modified by between-column distances (Fig. 6.6). At the extreme of within-column distance (12 feet), the significant negative autocorrelation at later ages understandably was not caused by direct competition of trees of interest, but through some complicated spatial processes (Fig. 6.9). The significant negative or positive autocorrelation at early ages for treatments with the within-row distance of twelve feet can only be attributed to unexplainable variations.

When the within-column distances were moderate (six or eight feet), the effects of between-column distance become more pronounced (Figs. 6.7 - 6.8), as evidenced by more diverse patterns.

Apparently autocorrelation was not only dependent upon the distances between trees being considered, but upon the spacing of a whole stand. A spatial pattern could be generated by the interrelations of neighborhood effects when stand competition materializes.

It can be assumed that loblolly pine trees generally tended to build symmetric tree geometry, including crown and root system. Wherever between-column distance or within-column distance became too short, tree growth was influenced, as evidenced by the significantly negative spatial autocorrelation. However, certain plasticity about tree architectures existed as a result of avoiding direct growth resource competition, which was substantiated by the autocorrelation test in rectangularly spaced plots, for example, 12 * 6, and 12 * 4 ft.

Autocorrelation could be generated by the direct intertree competition. At the same time one could also detect the autocorrelation which was purely a results of interrelations of neighborhood effects. The autocorrelation indices with the first, second and third order neighbors were illustrated (Fig. 6.10). The dynamics of Moran Z proved to be very similar for the neighbors of the first degree and for those of the third degree. Although we can assume that negative spatial autocorrelation is a result of competition, the insignificant positive Moran's I for the second-order neighbors and the significant negative autocorrelation with the third-degree neighbors can be more reasonably assumed to be a result of spatial autocorrelation processes.

Spatial patterns modelling.

The previous results indicated that there were some spatial patterns which would generate negative correlation for first order neighbors and for third degree neighbors, but positive autocorrelation for second order neighbors, which suggested that the spatial pattern was oscillatory. However, modelling with Equation [6.11] was not satisfactory. The Fourier models could only yield significant

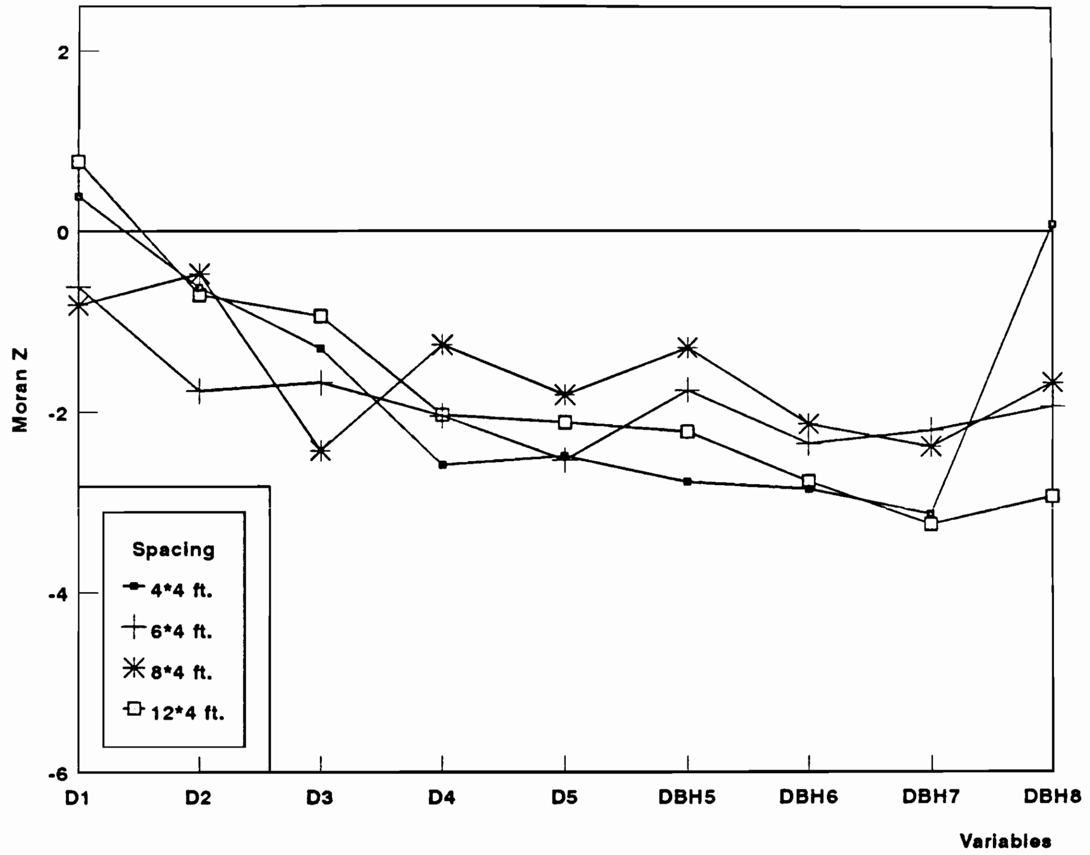

Figure 6.6. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: within-column distances fixed as four feet.

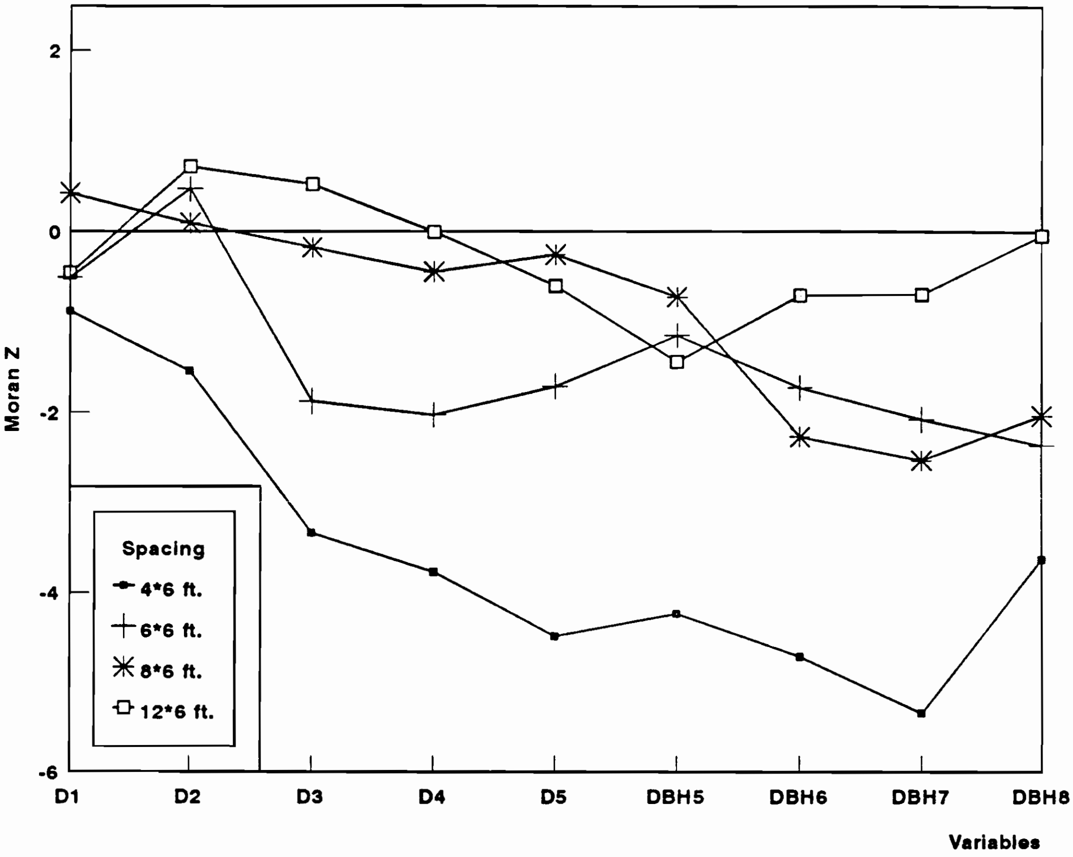

Figure 6.7. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: within-column distances fixed as six feet.

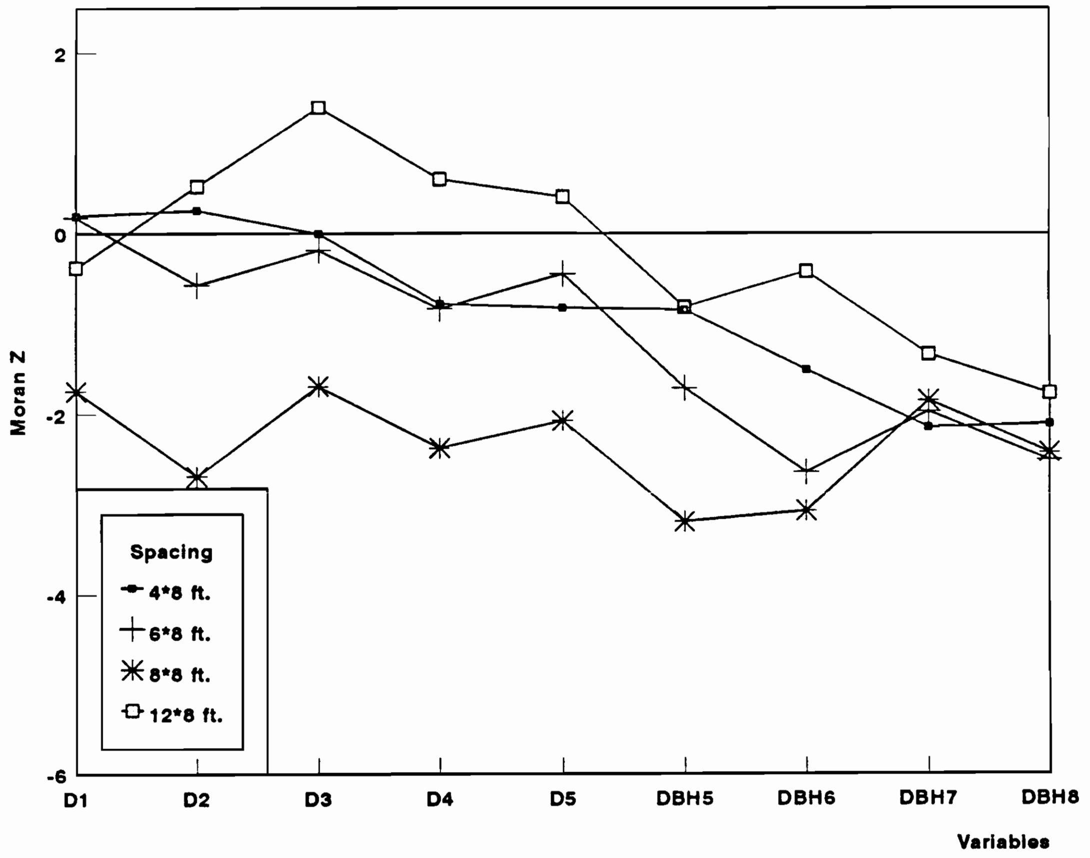

Figure 6.8. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: within-column distances fixed as eight feet.

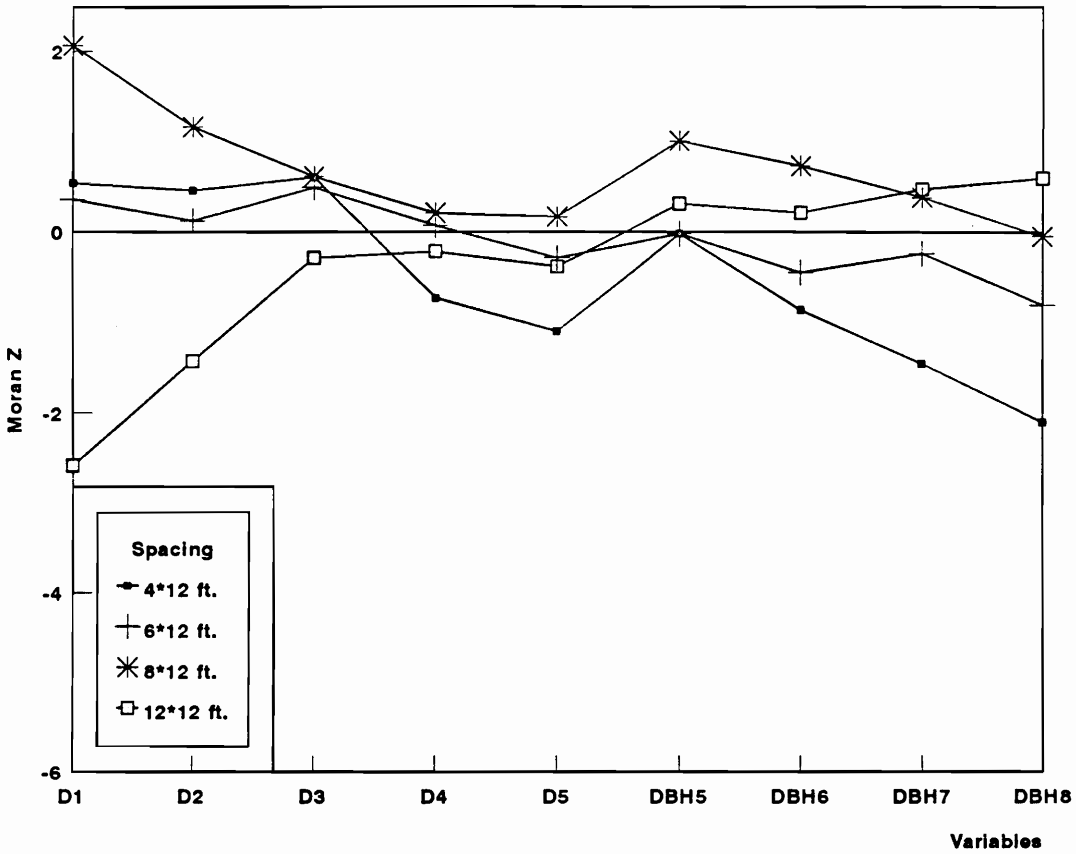

Figure 6.9. Spatial autocorrelation tests of diameter measurements with Moran index under the normality assumption: within-column distances fixed as twelve feet.

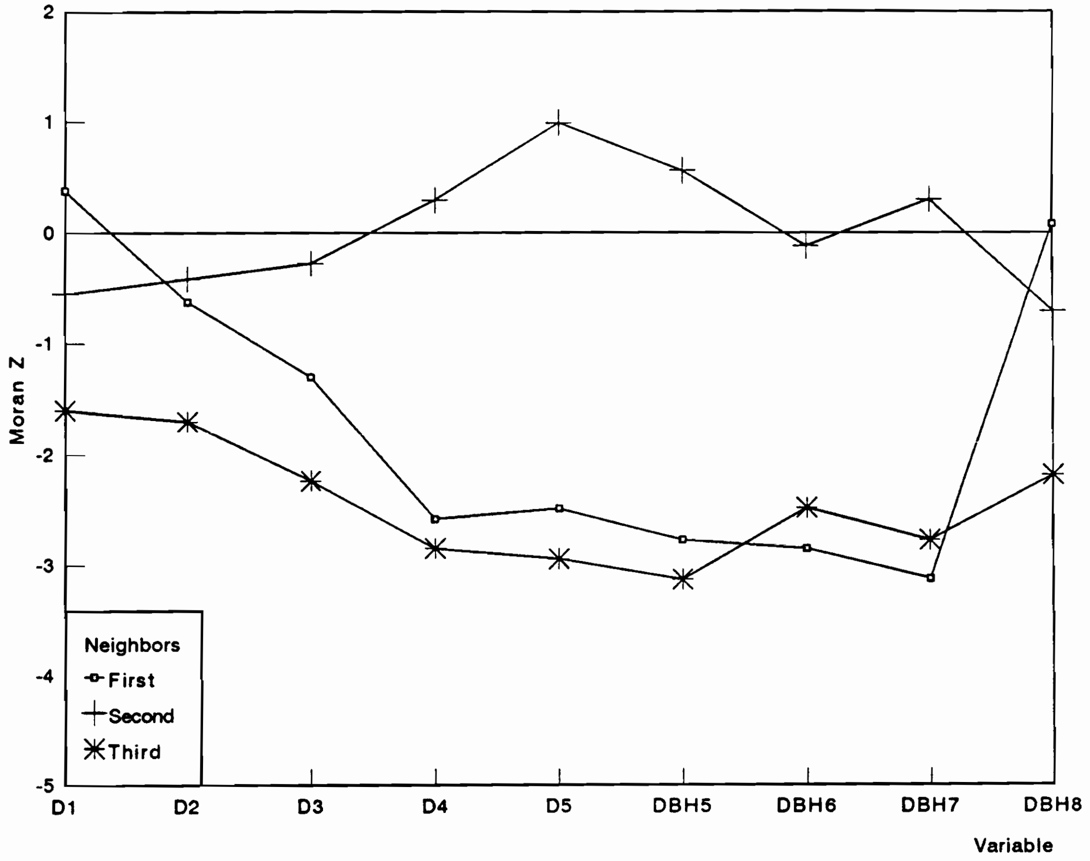

Figure 6.10. Spatial autocorrelation tests of diameter measurements with Moran index : spacing treatment 4 *4 feet.

fittings for high density treatments at the eighth remeasurement, which implied either that model was unsuitable or that spatial pattern was confounded with other sources of variations.

Autocorrelation of Total Height Measurement.

The Moran indices and their corresponding Z values were computed for the detrended total height measurement by Equation [6.2] for each of the spacing treatments under the normality assumption. The results were given in Table 6.4 and Table 6.5. Significant autocorrelation could be found for treatments with a within-row distance of four feet in the later years of stand growth. One may also find high negative autocorrelation for the spacing treatment of 4 * 6 feet, and significant negative autocorrelation indices in the spacing treatments 6 * 8 and 8 * 8 feet. It was perhaps more reasonable to assume that the high autocorrelation of total height was more a reflection of a allometric relationship between DBH and total height (Tables 6.2 - 6.3) than of an effect from neighborhood interference. It may be worth pointing out that total height growth is less affected by intertree competition than DBH. Comparison of Tables 6.2 and 6.4 revealed that the magnitude of autocorrelation indices for total height was much smaller than that for DBH. Significant autocorrelation generally occurred one or two year later (Table 6.4 and Table 6.5) for total height than for diameter measurements. However, general trends of autocorrelation dynamics on total height appeared to be similar to those on DBH, and were also related to intertree competition to a lesser degree.

Table 6.4. Moran indices of detrended total height measurements

	Height measurements[1]							
Spacing (ft.)	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8
4 * 4	-0.0574	-0.0376	-0.0553	-0.1042	-0.0898	-0.0962	-0.0913	-0.0107
4 * 6	-0.1073	-0.1007	-0.1352	-0.2040	-0.2053	-0.1893	-0.1803	-0.1102
4 * 8	-0.0015	0.0520	-0.0011	0.0106	0.0042	-0.0276	-0.0384	0.0457
4 * 12	-0.0699	0.0448	0.0621	0.0380	0.0492	0.0480	0.0272	0.0879
6 * 4	-0.0741	0.0096	-0.0416	-0.0340	-0.0531	-0.0164	-0.0276	-0.0217
6 * 6	0.0862	0.0398	0.0399	-0.0247	-0.0621	-0.0103	-0.0163	-0.0417
6 * 8	-0.1181	-0.0329	-0.0139	-0.0334	-0.0749	-0.1007	-0.0541	-0.0535
6 * 12	-0.0278	0.0073	0.0749	0.0433	0.0400	0.0466	-0.0029	0.0330
8 * 4	-0.0940	-0.0846	-0.0611	-0.0784	-0.0542	-0.0595	-0.0376	-0.0482
8 * 6	-0.0024	-0.0453	-0.0182	-0.0405	-0.0232	-0.0693	-0.1190	-0.1049
8 * 8	-0.0478	-0.1371	-0.1046	-0.1010	-0.1122	-0.1023	-0.0401	-0.0977
8 * 12	0.0359	0.0271	0.0433	0.0449	0.0627	0.0777	0.0841	0.0911
12 * 4	-0.0562	-0.1050	-0.1096	-0.0540	-0.0894	-0.0918	-0.1160	-0.1442
12 * 6	-0.0326	0.0021	-0.0034	-0.0053	-0.0856	-0.0335	-0.0117	-0.0053
12 * 8	0.0050	0.0342	0.0023	-0.0340	-0.0232	-0.0493	-0.0561	-0.0706
12 * 12	-0.0637	-0.0381	-0.0463	-0.0352	-0.0144	-0.0716	-0.0172	-0.0028

[1] Where, H_1 is the total height at the first measurement,
H_2 is the total height at the second measurement, etc.

Table 6.5. Moran indices Z of detrended total height measurements under the normality assumption

	Height measurements[1]							
Spacing (ft.)	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8
4 * 4	-1.2535	-0.7985	-0.1898	-2.2725	-1.9434	-2.0820	-1.9603	-0.1576
4 * 6	-2.3748	-2.1899	-2.9383	-4.4526	-4.4672	-4.1149	-3.9102	-2.1714
4 * 8	-0.0056	1.1935	0.0131	0.0272	0.1304	-0.5696	-0.8076	0.9126
4 * 12	-1.5329	1.0217	1.3992	0.8654	1.1094	1.0784	0.6284	1.7314
6 * 4	-1.6271	0.2523	-0.8854	-0.7179	-1.1399	-0.3235	-0.5671	-0.3692
6 * 6	1.9758	0.9201	0.9175	-0.5038	-1.3249	-0.1867	-0.3177	-0.7446
6 * 8	-2.6173	-0.6807	-0.2686	-0.7003	-1.6204	-2.1895	-1.1546	-0.9675
6 * 12	-0.5865	0.2007	1.6868	0.9889	0.9149	1.0581	-0.0256	0.6773
8 * 4	-2.0757	-1.8552	-1.3216	-1.7006	-1.1565	-1.2728	-0.7880	-0.8750
8 * 6	-0.0149	-0.9614	-0.3529	-0.8327	-0.4597	-1.4484	-2.5142	-1.9401
8 * 8	-1.0373	-3.0270	-2.2920	-2.2075	-2.4551	-2.2255	-0.8478	-1.8366
8 * 12	0.8454	0.6428	0.9990	1.0288	1.4149	1.7376	1.8760	1.7773
12 * 4	-1.2260	-2.2886	-2.3818	-1.1513	-1.7098	-1.9742	-2.4890	-2.6935
12 * 6	-0.6947	0.0860	-0.0369	-0.0770	-1.8154	-0.6831	-0.2124	-0.0573
12 * 8	0.1504	0.8080	0.0898	-0.7219	-0.4789	-1.0566	-1.2087	-1.3161
12 * 12	-1.3935	-0.8056	-0.9834	-0.7359	-0.2789	-1.5357	-0.3385	-0.0095

Note: $p = 0.10$ for $Z = -1.645$.
$p = 0.05$ for $Z = -2.000$.
$p = 0.1$ for $Z = -2.58$.

[1] Defined in Table 6.4.

Conclusions

One may conclude from the previous results and discussion:

1. Significant autocorrelation could be found for the juvenile period of loblolly pine plantations. The systematic environmental gradients had a major impact on the spatial patterns of DBH and total height measurements, especially at the seedling period. This phenomenon has also been observed by Schoonderwood and Mohren (1987) when they studied the relationship between autocorrelation and competition in even-aged Douglas-fir stands in the Netherlands. Therefore, the spatial pattern produced by intertree competition was confounded with positive spatial autocorrelation generated by environmental gradients. Some detrending techniques have to be employed before investigating competition effects.
2. Both the Moran index and the Geary index could be used to describe autocorrelation and to test significance. However, with the dataset used in this study, the Moran index generally behaved better since it was not as sensitive to extreme values as the Geary index. Both the normality assumption and the randomization assumption produced similar results, although the results were consistently more conservative with the randomization assumption. The variance formula with the Geary index may not be estimable, because negative values will occur occasionally under the randomization assumption.
3. Intertree competition was evident in the autocorrelation measures, which increased with increased density and with stand ages. Tree-pair distance was a very important factor affecting the magnitude and the significance of Moran indices. Significantly negative autocorrelation could be detected as early as age 4 where the intertree distance was four feet. When the intertree distances were increased, the year that negative correlation appeared became delayed. In the extreme of intertree distance of twelve feet, significant negative autocorrelation only appeared when the stands were eight years old and where the distance to the nearest, unassociated neighbors was four feet. The research with Douglas-fir (Schoonderwoerd and

Mohren 1987) also pointed out that the occurrence of negative correlations depends on competition, as well as on the applied thinning regimes.

4. Autocorrelation depended on factors other than distances between associated tree pairs. The distances from other trees not in pairs also played an essential role. With within-column distance fixed, the autocorrelation indices were related to the between-column distance. The result suggested that a stand growth model with only Hegyi type competition indices was not enough to account for competition effects for individual tree growth. The overall competition level is also important and should be included in growth models. Trees tended to develop symmetric architectures for their crown and root systems. Wherever either row or column distances were so short that normal growth was retarded, significant autocorrelation would occur. However, in rectangularly spaced treatments, trees appeared to avoid competition by exploiting available growth resource, as evidenced by less significant or insignificant autocorrelation test. Trees in rectangular spacing probably have asymmetric crown and/or root system structures.
5. The competition process generated spatial patterns for DBH and total height measurements, which seemed to act in an oscillatory manner. However, even a Fourier type function was not adequate to describe them.
6. Total height growth was also subject to intertree competition. When the within-column distance was four feet, the autocorrelation indices were found to be statistically significant when the stand age was five years or older. However, total height growth was obviously less susceptible to competition than DBH growth, as indicated by the reduced frequency of significant Moran indices and by the smaller magnitude of the indices.

Chapter 7. Spatial Statistical Characteristics of DBH, total Height Increment and Competition Measures in Stand Simulators for Loblolly Pine (*Pinus taeda* L.) Stands

Introduction and Literature Review

Competition measures have long been of interest to plant ecologists and foresters, since an understanding of competition is helpful to predicting forest growth and yield accurately. In fact, accounting for competition effects has been an essential step for building most individual tree based growth simulators (Amateis *et al.* 1989, Burkhart *et al.* 1987, and Nance *et al.* 1987.). Furthermore, competition measures have been used for assessment of forest pest damage, and as criteria for vegetation management and advanced generation selection in genetic improvement research (O'Sullivan *et al.* 1985, Tuscan and McKinley 1984, Wagner and Radosevich 1988). Measures of competition intensity can be conveniently grouped either into measures of average stand competition, or point competition measures, depending on whether they describe average overall crowding or the competitive stress affecting a particular plant. The key difference between the stand level and point competition measures lies in whether the spatial distribution within a stand is accounted for explicitly. Within the category of point competition indices, there are two subcategories of competition indices. One subcategory, called distance dependent competition measures, incorporates the number, dimension and location of certain neighbors. Another, called distance independent competition measures, includes only a part of spatial information such as the size of neighbors.

Stand level competition measures.: Naturally the most obvious measure for stand level competition is the number of plants per unit area. This is in fact the most commonly used index in plant ecological research. Its principal advantage is its ease of measurement and interpretation. However the weakness of the number of plants per unit area is also very obvious. Especially in forestry, size of trees varies widely so that this alone can not adequately describe the stand competition stress. In order to overcome this difficulty, many density measures have been proposed and used. Clutter *et al.* (1983) summarized the previous works. Their list included: 1) number of trees per unit area; 2) basal area per unit area; 3) stand density index; 4) tree-area ratio; 5) crown competition factor; and 6) spacing index or relative spacing. Most measures assume a hypothesized 'growing space' as the competition target and have been successfully applied to modelling plant growth and survival. Although none of the known loblolly pine stand simulators relied only on stand level competition measures for individual tree projections, almost all of them included some density measures in survival functions or other components. They are useful in modelling the stand level distribution parameter dynamics (Chapter 4) and would be helpful to account for a part of spatial patterns as revealed in Chapter 6.

Point Competition Measures

Distance independent competition measures: Most of the distance independent competition measures consist of stand-level density measures and the subject tree dimension information. A typical measure, proposed by Glover and Hool (1979), is defined as:

$$G_i = \frac{DBH_i^2}{\overline{DBH}^2} \qquad [7.1]$$

where $\overline{DBH}$ is an arithmetic mean of stand DBH. This formula was later modified and $\overline{DBH}$ was replaced by $\overline{DBH_q}$ which is a mean of squared DBH. Amateis *et al.* (1989) used the latter version as a competition index surrogate when they developed diameter growth and survival equations. Later, a distance independent stand growth simulator prototype, TRULOB,[4] was built on this equation. Crown ratio, defined as the ratio of live crown length to total height, is a natural distance independent index of a tree's photosynthetic potential. It integrates the effects of competition and has been found to be highly related to growth (Daniels and Burkhart 1975, Daniels, Burkhart and Clason 1986, Leary 1979) and to mortality (Avila 1990). In fact, most of the loblolly pine stand simulators , such as TRULOB, PTAEDA2 (Burkhart *et al.* 1987), and PTAEDA2/APA,[5] utilized the crown ratio in one way or another.

Distance independent indices are easy to calculate and less demanding in data and in computer time. These indices may be sufficient in artificially regenerated plantations due to their regular spacing. Martin and Ek (1984) concluded that distance dependent competition indices showed little or no advantages over the distance independent competition indices after having compared various competition measures.

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[4] Amateis 1991, personal communication.

[5] Nance, W. L., and J. E. Grissom. 1989. PTAEDA/APA model outline (unpublished).

Distance dependent competition indices: Based on different philosophies, five families of distance dependent competition indices can be recognized:

Area overlap indices.
point density measures.
Distance weighted size ratios.
Area potentially available indices.
Sums of the angles from a subject plant to its neighbors.

Opie (1968) proposed the influence zone overlap index. The basic assumptions were that: a) a tree's total competitive ability for all resources could be represented by an influence circle or zone surrounding the tree with radius which is a function of tree size; b) the competitive stress experienced by a tree was a function of the degree to which its influence zone was overlapped by those of its neighborhood (Gerrard 1969, Keister 1971, Daniels 1976). Considering that plants are fixed in space and generally occupy a certain size of growing space, these two assumptions seem quite reasonable. Opie (1968) compared his index with other existing point density indices. His index helped to reduce the residual mean square of basal area growth and was slightly better than other measures.

Tomé and Burkhart (1989) developed some new versions and modifications of distance weighted size ratios and area overlap indices by separating dominant neighbors from suppressed ones and correlated them with yield data from a spacing study of eucalypt plantations, in conjunction with stand level variables. They found that the new versions performed generally better by the criteria of both simple correlation coefficients and growth prediction accuracy. Daniels (1976) evaluated and compared several competition indices on the basis of simple correlation with loblolly pine individual tree growth and multiple correlation with growth in the presence of other tree and stand attributes. His results demonstrated that all indices were significantly correlated with DBH and basal area growth. He concluded that APA (area potentially available) would be a good index for growth prediction models when other tree stand attributes are already known.

Pukkala and Kolström (1987) examined the effect of competition on radial growth of Scots pine (*Pinus sylvestris* L.) with 12 competition indices. About 20% of the variation in radial growth in a five year period could be explained by their indices. The relative effectiveness of competition measures was not consistent across stands and stand ages. Furthermore, Pukkala (1988) developed an index based on ecological field theory (Wu *et al.* 1985, Walker *et al.* 1989). When combined with an individual tree diameter and height, both conventional indices and that index could account for 82-84% of basal area growth variation over a five year period. The competition index which was based on ecological field theory proved to be a little more effective than the traditional indices in predicting the within stand growth variation . Whether this small gain can justify the complexity of the index computation is still an open question.

Weiner (1984) found that the size of neighbors was the most important single variable on individual tree yearly diameter growth in a study in a young *Pinus rigida* stand. His competition index was a Hegyi type index and had a coefficient of determination of 0.21 - 0.48 with growth rate. PTAEDA2, an individual loblolly pine tree growth and stand development simulator (Burkhart *et al.* 1987), applied the same index, given as:

$$CI_i = \sum_{j=1}^{n} (DBH_j/DBH_i)/DIST_{ij} ; \qquad [7.2]$$

where;

CI_i	Competition index for subject tree i.
n	The number of competitors on subject tree i.
DBH_i	The diameter at breast height for tree i.
$DIST_{ij}$	The distance between subject tree i and its competitor j.

Bella (1971) assumed that the influence zone of each tree was a function of its size and that the amount and nature of interaction depended on the distance between and relative size (or power of it) of a subject tree and its competitors. His model of influence zone overlap behaved well for pure, even-aged, fully stocked stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco.), Jack pine (*Pinus banksiana* Lamb.), red pine (*Pinus resinosa* Ait.) and aspen (*Populous tremendoises* Michx.) and for an even-aged stand of *Eucalyptus spp.* growing at a range of stand densities.

The Dirichlet polygon and its modification has also been used in vegetation research (Daniels *et al.* 1986, Pelz 1978, Nance *et al.* 1987). The Dirichlet procedure divides a plane containing scattered points into polygons so that sides of the polygon are equidistant between adjacent points. anywhere in a subsection around a point is closer to that point than to any other points in a plane (Green and Sibson 1978). Theoretically it is a very crude way to define 'area potentially available' (APA) since the area for each individual is only determined by the spatial distribution of its neighbors, regardless of its own size and its neighbor's sizes. However, Mithen, Harper and Weiner (1984) did find that the polygon area provided a reasonably good predictor of plant weight in greenhouse populations of *Lapsana communis* L. Nance *et al.* (1987) proposed a new class of APA indices which used the following tessellation function to place the perpendiculars between the subject tree and its competitor:

$$L_p = \min\left(\frac{DBH_s^2}{(DBH_s^2 + DBH_c^2)} \times L_{c,} \quad (\overline{CR}/CR_{\max}) \times CR_{open} \right) \qquad [7.3]$$

where:

L_p Distance from the subject tree to the perpendicular line forming an edge between the subject tree and a competitor;

DBH_s DBH of the subject tree;

DBH_c	DBH of a competitor.
L_c	Distance from the subject tree to a competitor;
$\overline{CR}$	Mean crown ratio of all trees in the stand;
$CR_{\max}$	Maximum attainable mean crown ratio for stands of the same species;
CR_{open}	The expected crown radius of an open-grown tree of the same species with DBH of the subject tree.

which simultaneously weighted tree sizes and constrained the maximum expansion of a tree's polygon in any one direction. Based on this new competition index, a version of PTAEDA2, called as PTAEDA2/APA, was developed.

Although indices of competition appeared to be based on different philosophies, and took many forms, the basic ideas were very similar in reality, especially for distance weighted size ratio (Hegyi 1974) and sums of the angles from a subject tree to its neighbors (Pukkala 1989). After the weighing and constraining, the APA competition measure by Nance *et al.* (1987), was very much similar to Opie's influence zone overlap index.

For timber management and for the prediction of stand growth and yield in particular, a measure of competition should be easily and objectively measured, biologically meaningful, and highly correlated with stand growth and yield (Clutter *et al.* 1983). Statistically, the inclusion of those measures in yield equations should help to make the error structure uncorrelated and to alleviate to a certain degree problems caused by autocorrelation (negative and/or positive).

From all the previous studies it seems that there are no universally superior competition indices and potential for further improvement is also limited if no consideration is taken of physioecological measurements (such as water and nutrient cycles of tree-air-soil subsystem) or systematic analysis of forest ecosystem are made. The choice of competition measures depends on the tree species, stand structure, and to a large extent, one's preference.

Previous investigations concentrated on designing better competition indices based on their ability to improve accuracy of growth projections only. An important aspect, the spatial statistical characteristics of individual tree simulators built with these competition measures, were largely ignored. A dependent observation carries less information than an independent observation in cases of spatial autocorrelation, since it is partly predictable from its neighbors. The presence of autocorrelation among the population error terms leads to biased estimates of the residual variance and inefficient estimates of the regression parameters when the method of ordinary least squares (OLS) is used (Cliff and Ord 1981). It was pointed out that predominantly positive correlations between the trees in a plot would cause the variance within a plot to be smaller than the variance for the stand, while negative correlations would have the opposite effect (García 1991). Therefore, any simulator, which gave unbiased prediction for means but yielded related error structures, could still not provide reliable and precise stand growth and yield projection. This aspect of stand growth simulators needs to be addressed.

Methodology

The tree lists from the control plots at plot establishment of the Coop thinning study were inputted into stand simulators TRULOB, PTAEDA2, and PTAEDA2/APA, and simulated at six and nine year intervals separately. The corresponding tree lists were outputted. Then, the outputs were combined with the remeasurement data, and the prediction residuals, defined as:

$$\text{Residual} = \text{Predicted} - \text{Observed}, \qquad [7.4]$$

were computed. Since TRULOB did not use any information of tree coordinates, its performance will be compared with those of simulators using distance dependent competition measures, *i. e.* , PTAEDA2 and PTAEDA2/APA.

Other variables examined for spatial statistical characteristics were increments of the observed DBH and total height.

The Moran index were computed in order to examine the significance of spatial autocorrelation. A weight matrix, which was present in Equation [6.3] as w_{ij} were defined. Since one of the objectives of this study was to determine the error structure behaviors of stand simulators, the same point sampling method was used to select competitors as used in PTAEDA2. For a subject tree i, competitors were those trees which could be selected from tree i with a BAF of 10 ft^2 per acre. If tree j was selected, w_{ij} was assigned the value of 1. The Moran index, defined as in equation [6.3], and the corresponding Z values under the normality assumption, were computed for each plot.

Results and Discussions

Spatial characteristics of prediction residuals of three simulators.

Ideally, the prediction residuals should exhibit none of the spatial pattern, *i. e.*, not only unbiased, but also spatially accurate. Otherwise, the estimate of standard errors, and the corresponding confidence interval would not be reliable due to inter-correlated error structures. The estimates of the Moran indices and their significance tests under the normality assumption were are in Appendix B (Tables B.1 - B.4). The number of plots with significant spatial residual patterns is listed in Table 7.1 and Table 7.2.

None of the stand growth models performed perfectly. Some significant spatial autocorrelation could be found in a few plots no matter which model was employed. However, it was obvious that PTAEDA2, a growth model built with Hegyi type distance dependent competition index, did the best job both for DBH and total height projections from the point of view of spatial statistical properties. Among the plots tested, residuals in about 16.8% plots were detected to be significantly autocorrelated for DBH projection over a six year interval by PTAEDA2, compared to about 29.0% by TRULOB and 38.7% by PTAEDA2/APA. Fewer plots with spatial autocorrelation were found for total height projection residuals. PTAEDA2 yielded significant residual patterns in 13 plots over a six year period, and PTAEDA2/APA in 14 and TRULOB in 32 correspondingly. Comparison of TRULOB and PTAEDA2/APA are inconclusive. TRULOB, with a distance independent competition index, generated more significant spatial patterns for total height projections over both six and nine year intervals, and for DBH over a six year interval. But, PTAEDA2/APA yielded more spatially patterned residuals for DBH over a six year interval than TRULOB. The incorporation of tree coordinates significantly helped PTAEDA2 to produce desirable error structures in most cases. One may conclude that the distance dependent competition measures

Table 7.1. Number of plots where tests of spatial autocorrelation are significant for 6 year DBH and total height projection residuals

	Model					
	TRULOB		PTAEDA2		PTAEDA2/APA	
Significance	DBH	Height	DBH	Height	DBH	Height
Positive	43	30	25	10	60	14
Negative	2	2	1	3		
Combined	45	32	26	13	60	14

Significance at $\alpha = 0.10$.
A total of 155 plots tested.

Table 7.2. Number of plots where tests of spatial autocorrelation are significant for 9 year DBH and total height projection residuals

	Model					
	TRULOB		PTAEDA2		PTAEDA2/APA	
Significance	DBH	Height	DBH	Height	DBH	Height
Positive	3	14	1	8		10
Negative					2	
Combined	3	14	1	8	2	10

Significance at $\alpha = 0.10$.
A total of 45 plots tested.

produced better residual structures, i. e., less spatially dependent on average than the distance independent competition measure in this simulation.

The more positively correlated significant residual patterns indicated that errors of predictions occurred systematically in a plot, *i.* e., a tree with underprediction had neighbors which also were underpredicted, and *vice versa.* This was especially true for DBH prediction by PTAEDA2/APA over a six year interval. These findings strongly suggested that accounting for systematic environmental variation in a plot has more potential than improving competition measure for enhancing the performance of stand growth simulators both in the sense of more accurate prediction and of more desirable error structures.

Spatial patterns of DBH and total height increment.

In order to predict tree growth accurately and to devise better competition models, the growth pattern needs to be examined. The six year and nine year increment of DBH and total height was analyzed with the Moran index and the results were given in Appendix B (Tables B.5 - B.6), and the numbers of plots with significant spatial pattern were summarized in Table 7.3.

By allometric laws, DBH is highly related to total height. Therefore, the increment of total height should also be highly related to the increment of DBH. However, the spatial pattern of total height was different from the patterns of DBH increment in many cases as indicated in Table B.5 and Table B.6. At an α level of 0.10, 36 plots from a total of 155 were found to be positively correlated spatially for six year increment of total height. However, among the 36 plots, only one plot had been detected to be positively correlated spatially on DBH increment measurements. The spatial autocorrelation tests for the nine year increment was consistent with the tests for the six year increment. Among the seven plots with significant ($\alpha = 0.10$) positive spatial autocorrelation on total height increment, only one of them was determined to be spatially positively autocorrelated on

Table 7.3. Number of plots where tests of spatial autocorrelation are significant for DBH and total height increment

		Variable			
		HEIGHT		DBH	
Interval	Significance	$\alpha = 0.10$	$\alpha = 0.20$	$\alpha = 0.10$	$\alpha = 0.20$
6 years	Positive	36	52	9	14
	Negative	0	2	3	13
9 years	Positive	7	9	2	4
	Negative	0	2	2	6

A total of 155 plots for six year interval tested.
A total of 45 plots for nine year interval tested.

DBH increment. Table 7.2 showed that the number of plots with significant autocorrelation for DBH and total height increment at both $\alpha = 0.10$ and $\alpha = 0.20$ levels. The striking difference between spatial characteristics of DBH increment and total height increment was that there were far more positive autocorrelation plots, and far fewer negative autocorrelation plots with the former variable. There were 36 plots with significant positive autocorrelation ($\alpha = 0.10$), and none with negative autocorrelation for six year interval total height increment. As a contrast, nine plots were seen to be spatially positively correlated and another three to be spatially negatively correlated on DBH increment during the same growth period. If the α level is set at 0.20 in consideration of the small sample size, this contrast is more obvious. For total height increment over a six year interval, 52 plots had positively spatially correlated patterns, only two plots had negatively spatially correlated patterns. The numbers of plots with significant spatial patterns for DBH increment were almost equal for each sign, positive for 14 plots and negative for 13 plots. Among the 45 plots tested for the nine year interval increment, more plots with positively correlated patterns could also be found for the total height increment measurement (7 at $\alpha = 0.10$, and 9 at $\alpha = 0.20$), as opposed to the DBH increment measurement (2 at $\alpha = 0.10$, and 4 at $\alpha = 0.20$). Significant negative autocorrelation appeared more often with DBH increment (2 at $\alpha = 0.10$, and 6 at $\alpha = 0.20$) than with total height increment (none at $\alpha = 0.10$, and 2 at $\alpha = o.20$).

The studies on spatial characteristics of juvenile loblolly pine plantations (Chapter 6) showed that nearly 40 percent of the plots had significant systematic variation in their diameter measurements during the early years of stand development, which may be attributable to the systematic environmental variations. Therefore, significant positive spatial patterns could be attributed to the microsite variation effects on increment of total height. However, the disparity of spatial statistics between the DBH and total height increments seemed incompatible with the hypothesis that environmental variation caused the positive autocorrelation of total height increment. If environmental variation is the main source, the increment of DBH should generate spatial patterns similar to those of the increment of total height, as dictated by the allometric law. An alternative explanation is that competition processes generate positively autocorrelated spatial patterns on total height growth under certain circumstances. In other words, height growth reacts to competition positively, which is in contrast with the findings of Burkhart *et al.* (1987).

The dilemma suggested the need for further analysis of the response of total height to competition, and how it differs from diameter growth responses. Thus, growth data were divided into two datasets, one, being designated as Dataset 1, including only trees from plots where positive autocorrelation was found to be significant for total height growth (Table B.5 and Table B.6); Dataset 2 contained the remaining data. Using the function cited in Equation [5.11], the effect of competition on total height and basal area growth was modeled with the Hegyi competition index

Table 7.4. **Parameter estimates and fit statistics of modelling response of total height and basal area growth over a six year interval to competition level**

		Dataset 1	Dataset 2
	n	54	326
Total Height (m)	α	1.5610	1.6345
	β	1.8011	1.4051
	R^2	0.1707	0.1562
Basal Area (cm^2)	α	4.8515	5.1059
	β	4.0206	4.0848
	R^2	0.3701	0.4852

defined in Equation [7.2], with the competitors chosen at BAF of 10. The results are given in Table 7.4.

The significant, and negative, relationship between height growth and competition measures clearly refuted the hypothesis that competition processes stimulated positive spatial patterns on total height increment. Height growth of loblolly pine trees either from plots with significant positive spatial pattern on height increment or those without it responded more or less in the same manner, *i. e.*, height growth was hampered by intertree competition. However, it was found that only a very small portion of the variation in total height growth could be accounted for by the competition measure (17.07% for Dataset 1 and 15.62 % for Dataset 2), but that a higher percentage of basal area growth was explained (37.01% for Dataset 1 and 48.53% for Dataset 2). Also a larger percentage of basal area growth variation was accounted for by competition effects in Dataset 2 than in Dataset 1. All these results implied that growth of both DBH and total height was confounded by competition effects and microsite quality. If microsite variation was small, more variation of

DBH increment could be accounted for by competition effects, from which in turn one may infer that plots in Dataset 1 have large microsite variation. Since total height is less influenced by inter-tree competition, the increment is dominated by microsite variations to a larger degree. Therefore, positive autocorrelation patterns would appear more often. Nonetheless, because DBH growth is more susceptible to neighborhood competition, effects of microsite quality are alleviated to some degree, resulting in negative or insignificant spatial patterns.

Reviews of Competition Accounting for Both DBH and Total Height Growth Prediction.

TRULOB and PTAEDA2 used the same mechanism to simulate tree growth. Basically, total height growth is given by:

$$HIN = PHIN(b_1 + b_2 CR^{b_3} e^{(-b_4 CI - b_5 CR)}); \qquad [7.5]$$

Where;

HIN	Height increment.
PHIN	Potential height increment, which is derived from the site index equations.
CR	Crown ratio.
CI	competition index, defined as Equation [7.1] for TRULOB and as Equation [4.2] for PTAEDA2.
b_1 - b_5	parameters estimated from the data.

and then, potential diameter increment were estimated by:

$$PDIN = 0.286583 HIN + 0.209472. \qquad [7.6]$$

Afterwards, DBH growth was driven by:

$$DIN = PDIN(b_1 CR^{b_2} e^{b_3 CI}) \qquad [7.7]$$

and was based on the potential diameter growth, which in turn depended on potential height growth (Burkhart *et al.* 1987, Amateis *et al.* 1989). This approach proved successful for prediction of stand growth in general. However, from the point of view of error structure, one shortcoming can be easily recognized. This set of functions did not take a tree's original status in a stand into consideration. A tree, which was taller at the beginning of a growth period, has a high probability of growing more rapidly than its shorter neighbors since it already occupied a superior position over its competitors. The variation of tree size at the beginning could be attributable either to intertree competition or to systematic environmental variation. If some method could be found to account for the relative status, which might be considered as a surrogate of microsite quality index, in height growth functions, that part of the positive correlated error structure problem might be alleviated.

The serial sequence of developing height and diameter growth functions resulted in the unbalanced performance on error structures between DBH and height projections. In other words, PTAEDA2 did a much better job on total height projection than on DBH projections based on the criterion of residual spatial patterns. Simultaneously building compatible DBH and height functions may be a solution.

We have seen that the spatial pattern of height growth was often positive. The three loblolly pine stand growth simulators also yielded positive spatial patterns in most cases. These findings suggested that efforts currently focusing on improving competition measures should perhaps be shifted to addressing microsite effects.

Conclusions

Only three loblolly pine simulators were examined for their spatial characteristics of projection. These comparison are far from complete. The author hopes that researcher's attention will be brought to this topic and some new criteria will be used to judge competition indices. One may conclude from the foregoing discussions:

1. TRULOB and PTAEDA2 were two comparable models different somewhat in their competition index. PTAEDA2 generated far fewer plots with significant autocorrelation error structures. This may suggested that the distance dependent competition index helped in making the error structures of model building and prediction statistically more desirable, and in obtaining more reliable confidence intervals of predictions. Since the DBH growth functions in TRULOB and PTAEDA2 were developed using information from total height growth functions, more significant residual patterns occurred with DBH measurement than with total height measure. Perhaps simultaneous regression techniques could be employed to develop compatible growth functions for related size measurements in further modelling processes in order to eliminate the disparity of error structures between DBH and total height.
2. More positive error structures occurred with prediction residuals of both DBH and total height by the three growth simulators examined than negative error structures. This clearly indicated that the three models failed to account for the systematic environmental variations in a plot. A possible approach has been proposed to consider the relative status of one tree in computing growth rate. In this way, some microsite variation might be accounted for if a tree list could be provided for simulation.
3. Increment of DBH and total height exhibited significant spatial patterns. The spatial pattern of total height increment appeared different from the pattern of DBH. Most of the spatial patterns with total height increment were positive, while the numbers of plots with statistically significant autocorrelation are almost identical for both signs (positive and negative) for DBH

increment. These phenomena may be attributable to the differential responses of DBH and total height growth to competition effects. Less that 20% of total height growth variation could be explained by competition levels. Yet about 40% of basal area growth variation could. The differential responses led to different spatial patterns for these two variables.

4. The more positive residual patterns and positive spatial patterns for tree growth clearly demonstrated the need for more research into the nature of microsite variation, both for more accurate prediction and for more desirable error structure. Currently, attention has been focusing on devising and modifying competition measures, which is justifiable and important. However, discriminating treatments towards DBH and total height, and adequate description of micrositic variations in growth simulators seem more important.

Bibliography

Amateis, R. L., H. E. Burkhart, and T. A. Walsh. 1989. Diameter increment and survival equations for loblolly pine trees growing in thinned and unthinned plantations on cutover, site-prepared lands. Southern Journal of Applied Forestry 13: 170-174.

Amateis, R. L., H. E. Burkhart. 1987. Tree volume and taper of loblolly pine varies by stand origin. Southern Journal of Applied Forestry 11: 185-189.

Amateis, R., H. E. Burkhart and S. M. Zedaker. 1988. Experimental design and early analysis for a set of loblolly pine spacing trials. in Forest Growth Modelling and Prediction. USDA For. Ser. Gen. Tech. Rep. NC-120. pp 1058-1065.

Avila, O. 1990. Survival equations for loblolly pine trees in cutover, site-prepared plantations. M.S. thesis, Virginia Polytechnic Institute and State university.

Baker, F. S. 1950. Principles of silviculture. McGraw-Hill BooK Company, Inc., New York.

Barnes, A. 1982. Variability and uniformity in vegetable research. Internal Report National Vegetable Research Station, Wellesbourne, Warwick, UK.

Bartlett, M. S. 1978. Nearest neighbour models in the analysis of field experiments. Journal of Royal Statistics Society 40:147-174.

Bartlett, M. S. 1975. The statistical analysis of spatial pattern. Chapman and Hall, London.

Begon, M. 1984. Density and individual fitness: asymmetric competition. In Evolutionary ecology. Ed. by B. Shorrocks. Blackwell Scientific Publications, Ltd., Oxford. PP. 175-194.

Bella, I. E. 1971. A new competition model for individual trees. Forest Science 17: 364-372.

Benjamin, L. R. 1984. The relative importance of some sources of root-weight variation in a carrot crop. Journal of Agricultural Science 102: 69-77.

Benjamin, L. R. and N. Bell. 1985. The influence of seed type and plant density on variation in size of red beet(*Beta vulgaria* L.) crops. Journal of Agricultural Science 105: 563-571.

Benjamin, L. R. 1988. A single equation to quantify the hierarchy in plant size induced by competition within monocultures. Annals of Botany 62: 199-214.

Benjamin, L. R. and R. C. Hardwick. 1986. Sources of variation and measures of variability in even-aged stands of plants. Annals of Botany 58: 757-778.

Bennett, F. A. and J. L. Clutter. 1968. Multiple-product yield estimates for unthinned slash pine plantations -- pulpwood, sawtimber, gum. U. S. Forest Serv. Res. Paper SE-35, Southeast Forest Exp. Sta., Asheville, N. C. 21p.

Biging, G. S. and M. Dobbertin. 1989. Spatial pattern analysis and competition for California mixed forests. in Forest Statistics, the proceedings of the conference on forest statistics in 1989. Ed by D. R. Pelz. Univ. of Freiburg, Freiburg, Germany.

Borough, C., D. J. Gates and R. McMurtie. 1980. Skewness reversal of DBH in *Pinus radiata* plantations. preprint.

Brand, D. G. and S. Magnussen. 1988. Asymmetric, two-sided competition in even-aged monoculture of red pine. Canadian Journal of Forest Research 18: 901-910.

Brand, D. B., Weetman, G. F. and P. Rehsler. 1987. Growth analysis of perennial plants: the relative production rate of its yield components. Annals of Botany 59: 45-53.

Bulmer, M. G. 1967. Principles of Statistics, 2nd Ed. The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Burkhart, H. E. 1987. Data collection and modelling approaches for forest growth and yield prediction. In: Predicting Forest Growth and Yield: Current Issues, Future Prospects (H. N. Chappell and D. A. Maguire, Eds.). College of Forest Resources, University of Washington, Institute of Forest Resources Contribution Number 58, pp. 3-16.

Burkhart, H. E., K. D. Farrar, R. L. Amateis, and R. F. Daniels. 1987. Simulation of individual tree growth and stand development in loblolly pine plantations on cutover, site-prepared areas. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, publ. FWS-1-87.

Burkhart, H. E. and P. T. Sprinz. 1984. A model for assessing hardwood competition effects on yields of loblolly pine plantation. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, publ. FWS-3-84.

Burkhart, H. E. and M. R. Strub. 1974. A model for simulation of planted loblolly pine stands. in Growth Models for Trees and Stand Simulation, the proceedings of IUFRO S4.01-4 meeting in 1973. Ed by J. Fries. Stockholm, Sweden.

Cannell, M. G. R., Rothery, P. and E. D. Ford. 1984. Competition within stands of *Picea sitchensis* and *Pinus contorta.* Annals of Botany 53: 349-362.

Cliff, A. D. and J. K. Ord. 1981. Spatial Processes; models & applications. Pion Limited. London.

Clutter, J. L. *et al.* 1983. Timber management: a quantitative approach, John Wiley & Sons, New York.

Clutter, J. L. and B. J. Allison. 1974. A growth and yield model for *Pinus radiata*in New Zealand. in Growth Models for Trees and Stand Simulation, the proceedings of IUFRO S4.01-4 meeting in 1973. Ed by J. Fries. Stockholm, Sweden.

Clutter, J. L. and F. A. Bennett. 1965. Diameter distribution in old-field slash pine plantations. Ga. Forest Res. Council Report 13.

Cormack, R. M. and J. K. Ord. 1979. Spatial and temporal analysis in ecology. Statistical Ecology, Volume 8. International Co-operative Publishing House, Fairland, Maryland.

Currah, I. E. 1975. Some factors affecting the size of plants in the carrot crop. Ph.D Thesis, University of London.

Daniels, R. F., H. E. Burkhart and T. R. Clason. 1986. A Comparison of competition measures for predicting growth of loblolly pine trees. Canadian Journal of Forest Research 16: 1230-1237.

Daniels, R. F. 1976. Simple competition indices and their correlation with annual loblolly pine tree growth. Forest Science 22: 454-456.

Daniels, R. F. and H. E. Burkhart. 1975. Simulation of individual tree growth and stand development in managed loblolly pine plantations. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, publ. FWS-5-75.

Davis, J. C. 1986. Statistics and data analysis in geology. John Wiley & Sons, New York.

Day, B. and R. A. Fisher. 1937. The comparison of variability in population having unequal means. An example of the analysis of covariance with multiple dependent and independent variates. Annals of Eugenics 7: 333-348.

Diggle, P. J. 1983. Statistical analysis of spatial point patterns. Academic Press, London.

Diggle, P. J. 1976. A spatial stochastic model of inter-plant competition. Journal of Applied Probability 13: 662-671.

Dyer, M. E. and H. E. Burkhart. 1987. Compatible crown ratio and crown height models. Canadian Journal of Forest Research 17: 572-574.

Ebdon, D. 1985. Statistics in geography. 2nd ed. Basil Blackwell, Oxford and New York.

Edmeades, G. O. and T. B. Daynard. 1979. The development of plant-to-plant variability in maize at different planting densities. Canadian Journal of Plant Science 59: 561-576.

Ek, A. R. and R. A. Monserud. 1974. Forest: A computer model for simulating the growth and reproduction of mixed species forest stands. Res. Rep. 2635, School of Natural Resources, University of Wisconsin - Madison.

Elfving, B. 1974. A model for the description of the structure in unthinned stands of Scots pine. in Growth Models for Trees and Stand Simulation, the proceedings of IUFRO S4.01-4 meeting in 1973. Ed by J. Fries. Stockholm, Sweden.

Fischer, R. A. 1973. The role of spatial pattern in the competition between crop plants and weeds. A theoretical analysis. Mathematical Biosciences 19: 335-350.

Ford, E. D. and P. J. Diggle. 1981. Competition for light in a plant monoculture modelled as a spatial stochastic process. Annals of Botany 48: 481-500.

Ford, E. D., 1976. The canopy of a Scots pine forest: description of a surface of complex roughness. Agricultural Meteorology 17: 9-32.

Ford, E. D. 1975. Competition and stand structure in some even-aged plant monocultures. Journal of Ecology 63: 311-333.

García, O., 1991. What is a diameter distribution? Presented at the IUFRO symposium on Integrated Forest Management Information Systems, Tsukuba, Japan, October 13-18, 1991.

Gates, D. J. 1982. Competition and skewness in plantations. Journal of Theoretical Biology 94: 909-922.

Gates, D. J. and Westcott, M. 1978. Zone of influence models for competition in plantations. Advance in Applied Probability 10: 499-537

Gerrard, D. J. 1969. Competition quotient: a new measure of the competition affecting individual forest trees. Michigan State Univ., Agricultural Exp. Stn., Res. Bulletin 20.

Getis, A. and B. N. Boots. 1978. Models of spatial processes. Cambridge University Press, London.

Glover, G. R. and J. N. Hool. 1979. A basal area predictor of loblolly pine plantation mortality. Forest Science 25: 275-282.

Green, P. J. and Sibson, R. 1978. Computing Dirichlet tessellations in the plane. Computer Journal 21: 168-173.

Gregoire, T. G. 1987. Generalized error structure for forestry yield models. Forest Science 33: 423-444.

Gregoire, T. G. 1985. Generalized error structure for forestry yield models fitted with permanent plot data. PH.D dissertation. Yale University.

Griffith, D. A. 1987. Spatial autocorrelation, A primer. Association of American Geographers, 1710 Sixteenth Street N.W., Washington, D. C.

Harper, J. L. 1977. Population Biology of Plants. Academic Press. London.

Hegyi, F. 1974. A simulation model for managing jack-pine stands. in Growth Models for Trees and Stand Simulation, the proceedings of IUFRO S4.01-4 meeting in 1973. Ed by J. Fries. Stockholm, Sweden.

Jenkins, G. M., and D. G. Watts. 1968. Spectral analysis and its applications. Holden-day. San Francisco.

Joliffe. P. A., A. N. Minjas and V. C. Runeckles. 1984. A reinterpretation of yield relationships in replacement series experiments. Journal of Applied Ecology 21: 227-243.

Jumars, P. A., Thistle, D. and M. L. Jones. 1977. Detecting two-dimensional spatial structure in biological data. Oecologia 28: 109-123.

Keister, T. D. 1971. A measure of the interspecific competition experienced by an individual tree in a planted stand. Louisiana State Univ., Agricultural Experimental Station, Bulletin No.652.

Koyama, H. and T. Kira. 1956. Intraspecific competition among higher plants. VIII. Frequency distribution of individual plant weight as affected by the interaction between plants. Journal of the Institute of Polytechnics, Osaka City University Series D 7: 73-94.

Kramer, P. J. and T. T. Kozlowski. 1979. Physiology of woody plants. Academic Press, New York.

Leary, R. A. 1979. Design. In: Generalized Forest Projection System Applied to the Lake States Region. USDA For. Serv. Gen. Tech. Rep. NC-49.

Lenhart, J. D. 1972. Cubic-foot yields for unthinned old-field loblolly pine plantations in the Interior West Gulf Coastal Plain. Stephen F. Austin State Univ., School of Forestry, Texas Forestry Paper No. 14, Nacogdoches, Tex.

Lenhart, J. D. and J. C. Clutter. 1971. Cubic foot yield tables for old-field loblolly pine plantations in the Georgia Piedmont. Ga. Forest Res. Council Report 22. -- Series 3, Macon, Ga.

Lin, J. Y. 1974. Stand growth simulation models for Douglas-fir and western hemlock in the North-western United States. in Growth Models for Trees and Stand Simulation, the proceedings of IUFRO S4.01-4 meeting in 1973. Ed by J. Fries. Stockholm, Sweden.

Mack, R. N. and J. L. Harper. 1977. Interference in dune annuals: spatial pattern and neighbourhood effects. Journal of Ecology 65: 345-363.

Magussen, S., 1989. Inter-plant interactions and their influence on within and among plot variances. Scandinavian Journal of Forest Research 4: 369-377.

Martin, G. L. and A. R. Ek. 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. Forest Science 30: 731-743.

McBratney, A. B. and R. Webster. 1981. Detection of ridge and furrow pattern by spectral analysis of crop yield. Int. Stat. Rev. 49: 49-52.

McGee, C. E. and L. Della-Bianca. 1967. Diameter distributions in natural yellow-poplar stands. USDA For. Serv. Res. Paper SE-25, Southeast Forest Exp. Sta., Asheville, N. C.

Mercer, W. B. and A. D. Hall. 1911. The experimental error of field trial. Journal of Agricultural Science 4 107-132.

Mithen, R., Harper, J. L. and J. Weiner. 1984. Growth and mortality of individual plants as a function of "available area". Oecologia 62: 57-70.

Myers, R. H. 1990. Classical and modern regression with applications. PWS-KENT Publishing Company, Boston.

Nance, W. L., J. E. Grissom, and W. R. Smith. 1987. A new competition index based on weighted and constrained area potentially available. in Forest Growth Modelling and Prediction. USDA For. Ser. Gen. Tech. Rep. NC 120. pp 134-142.

Naylor, R. E. L. 1976. Changes in the structure of plant populations. Journal of Applied Ecology 13: 513-521.

Neter, J., W. Wasserman and M. H. Kutner. 1990. Applied linear statistical models: regression, analysis of variance and experimental design. Richard D. Irvin, Inc., Homewood, IL.

Odland, J. 1988. Spatial autocorrelation. SAGE publications, Inc. Beverley Hills, California.

Onwin, D. J., 1975. An Introduction to trend surface analysis. Geo Abstracts, University of East Anglia, Norwich, NR4 7TJ, England.

Opie, J. E. 1968. Predictability of individual tree growth using various definitions of competing basal area. Forest Science 14: 314-323.

O'Sullivan, P. A., G. M. Weiss, and V. C. Dkoddatz. 1985. Indices of competition for estimating repeated yield loss due to Canada thistle. Canadian Journal of Plant Science 65: 145-149.

Pelz, D. R. 1978. Estimating individual tree growth with tree polygons. P. 172-178 in Growth models for long term forecasting of timber yields. J. Fries *et al.* (eds.). Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, publ. FWS-1-78.

Pukkala, T.,1989. Methods to describe the competition process in a tree stand. Scandinavian Journal of Forest Research 4: 187-202.

Pukkala, T. 1988. Methods to describe the competition process in a tree stands. in Studies on the Effect of Spatial Distribution of Trees on the Diameter Growth of Scot Pine. Ed. by Timo Pukkala. University of Joensuu, Joensuu, Finland.

Pukkala, T. and T. Kolström. 1987. Competition indices and the prediction of radial growth in Scots pine. Silva Fennica 21: 55-67.

Rabinowitz, D. 1979. Bimodal distributions of seedling weight in relation to density in *Festuca paradoxa* Desv. Nature 277: 297-298.

Reed, D. D. and H. E. Burkhart. 1985. Spatial autocorrelation of individual tree characteristics in loblolly pine stands. Forest Science 31: 575-587.

Renshaw, E. 1984. Competition experiments for light in a plant monoculture: An analysis based on two-dimensional spectra. Biometrics 40: 712-728.

Renshaw, E. and E. D. Ford. 1983. The interpretation of process from pattern using two-dimensional spectral analysis: Methods and problems of interpretation. Applied Statistics Series C 32: 51-63.

Ripley, B. D. 1981. Spatial Statistics. John Wiley & Sons, New York.

Roush, M. L., S. R. Radosevich, R. G. Wagner, B. D. Maxwell and T. D. Petersen. 1989. A comparison of Methods for measuring effects of density and proportion in plant competition experiments. Weed Science 37: 268-275.

Salter, P. J. 1985. Crop establishment: recent research and trend in commercial practice. Scientific Horticulture 36: 32-47.

Schoonderwoerd, H. and G. M. J. Mohren. 1987. Autocorrelation and competition in even-aged stands of Douglas-fir in the Netherlands. in Forest Growth Modelling and Prediction. USDA For. Ser. Gen. Tech. Rep. NC 120. pp 619-626.

Shainsky, L. J. and S. R. Radosevich. 1991. Analysis of yield-density relationships in experimental stands of Douglas-fir and red alder seedlings. Forest Science 37: 574-592.

Shapiro, S. S. and M. B. Wilk. 1965. An analysis of variance test for normality (complete samples). Biometrika 52: 591-611.

Short, E. A. III and H. E. Burkhart. 1992. Predicting crown-height increment for thinned and unthinned loblolly pine plantations. Forest Science. in press.

Simard, S. 1990a. Competition between Sitka alder and lodgepole pine in the Motane spruce zone in the south interior of British Columbia. FRDA report 150. pp. 1-26.

Simard, S. 1990b. A retrospective study of competition between paper birch and planted Douglas-fir. FRDA report 147. pp. 1-19.

Sokal, R. R. and N. L. Oden. 1978a. Spatial autocorrelation in biology 1. Methodology. Biological Journal of the Linnean Society 10: 199-228.

Sokal, Robert R. and N. L. Oden. 1978b. Spatial autocorrelation in biology 2. Some biological implication and four applications of evolutionary and ecologist interest. Biological Journal of the Linnean Society 10: 229-249.

Spitters, C. J. T. 1983. An alternative approach to analysis of mixed cropping experiments I. Estimation of competition effects. Neth. J. Agric. Sci. 31: 1-11.

Spurr, S. H. and B. V. Barnes. 1980. Forest Ecology. 3rd Edition. Wiley, New York.

Stern, W. R. 1965. The effect of density on the performance of individual plants in subterranean clover swards. Australian Journal of Agricultural Research 16: 541-555.

Tomé, M. and H. E. Burkhart. 1989. Distance-dependent competition measures for predicting growth of individual trees. Forest Science 35: 816-831.

Turner, M. D. and D. Rabinowitz. 1983. Factors affecting the frequency distribution of plant mass: the absence of dominance and suppression in competing monocultures of *Festuca paradoxa* . Ecology 64: 469-495.

Tuscan, G. A., C. R. McKinley. 1984. The use of competition indices in advanced-generation selection. Silvae Genetica 33: 209-215.

Wagner, R. G., S. R. Radosevich. 1988. Interspecific competition indices for vegetation management decisions in young Douglas-fir stands. Forestry Canada 26: 33-34.

Walker, J., Sharpe, P. J. H., Penridge L. K. and H. Wu. 1989. Ecological field theory: the concept and field tests. Vegetatio 83: 81-95.

Waller, D. M. 1985. The genesis of size hierarchies in seedling populations of *Impatiens capensis* Meerb. New Phytologist 100: 243-260.

Waller, D. M. 1981. Neighborhood competition in several violet populations. Oecologia 51:116-122.

Weiner, J. and S. C. Thomas. 1986. Size Variability and competition in plant monocultures. Oikos 47:211-222.

Weiner, J. 1985. Size hierarchies in experimental populations of annual plants. Ecology 66: 743-752.

Weiner, J. 1984. Neighbourhood interference amongst *Pinus rigida* individuals. Journal of Ecology 72: 183-195.

Weiner, J. and O. T. Solbrig. 1984. The meaning and measurement of size hierarchies in plant populations. Oecologia 61: 334-336.

Weiner, J. 1982. A neighborhood model of annual-plant interference. Ecology 63: 1237-1241.

Westoby, M. 1984. The self-thinning rule. Advanced Ecological Research 14: 167-225.

Westoby, M. 1982. Frequency distributions of plant size during competitive growth of stands: the operation of distribution-modifying functions. Annals of Botany 50: 733-735.

Whipple, S. D. and E. H. White. 1965. Response of planted loblolly pine following various conversion methods. Auburn University Agricultural Experiment Station Bulletin 362.

White, D. E. and M. Newton. 1988. Competitive interactions of whiteleaf manzanita, herbs, Douglas-fir, and ponderosa pine in southwest Oregon. Canadian Journal of Forest Research 19: 232-238.

Winer, B. J. 1971. Statistical principles in experimental design. 2nd Edition, New York: McGraw-Hill Book Co.

Wu, H., Sharpe, P. J. H., Walker, J. and Penridge, L. K. 1985. Ecological field theory: A spatial analysis of resource interference among plants. Ecological Modelling 29: 215-243.

Zutter, B. R., M. Perry, R. J. Mitchell, G. R. Glove, and D. H. Gjerstad. 1991. Competition among three perennial species: response of loblolly pine to gradients in sweetgum and broomsedge competition. Presented at the 45th Annual Meeting of SWSS, Little Rock, Arkansas. Jan. 20-22, 1992.

Appendix A. Tables of Distributional Parameters of Loblolly Pine Tree Size Variables

Table A.1. Mean parameters of stand distributions of ground line diameter

Parameter	Density	n	Plantation Age				
	ha^{-1}		1	2	3	4	5
Coefficient of Variation	6729	9	29.6425	29.1826	23.2530	21.9577	21.3139
	4485	18	29.9659	28.9577	22.5873	20.9895	19.5825
	3363	18	30.4086	29.0537	23.2347	21.6691	20.2621
	2990	9	28.0546	27.0972	21.2281	19.5275	18.4868
	2244	36	29.7214	27.6663	22.0778	19.9969	18.6322
	1683	9	29.1271	26.8021	21.8700	20.4366	18.8414
	1495	18	29.0296	27.9119	21.9005	19.7896	18.3254
	1122	18	30.4819	27.3582	21.5844	19.9983	18.0092
	749	9	29.2408	25.5394	19.6964	18.1858	17.0222
Gini	6729	9	0.1536	0.1569	0.1293	0.1177	0.0447
	4485	18	0.1585	0.1570	0.1267	0.1118	0.0412
	3363	18	0.1615	0.1573	0.1309	0.1168	0.0429
	2990	9	0.1543	0.1457	0.1187	0.1047	0.0388
	2244	36	0.1574	0.1493	0.1236	0.1072	0.0393
	1683	9	0.1536	0.1458	0.1225	0.1103	0.0399
	1495	18	0.1542	0.1505	0.1232	0.1059	0.0387
	1122	18	0.1607	0.1471	0.1204	0.1072	0.0379
	749	9	0.1568	0.1393	0.1116	0.0982	0.0362
Skewness	6729	9	0.3795	-0.2525	-0.5990	-0.7194	-0.7525
	4485	18	0.3515	-0.0502	-0.4332	-0.4683	-0.4483
	3363	18	0.3577	-0.0525	-0.2553	-0.3313	-0.3126
	2990	9	0.1670	0.0260	-0.3127	-0.3291	-0.3013
	2244	36	0.2826	-0.0387	-0.3563	-0.3585	-0.3857
	1683	9	0.1979	-0.1574	-0.4814	-0.4700	-0.5331
	1495	18	0.1016	-0.1755	-0.3058	-0.4606	-0.4823
	1122	18	0.4044	-0.0315	-0.2928	-0.2838	-0.2779
	749	9	0.4063	-0.2003	-0.4315	-0.5254	-0.5167
Kurtosis	6729	9	0.3160	0.3943	0.8197	1.0334	1.2655
	4485	18	0.2126	-0.0098	0.5665	0.8039	0.6274
	3363	18	0.0141	-0.1915	0.1680	0.4157	0.3886
	2990	9	-0.5537	-0.0295	0.2911	0.2058	0.5703
	2244	36	0.1466	0.0113	0.3103	0.5822	0.5197
	1683	9	-0.0740	-0.2058	0.2971	0.3534	0.5749
	1495	18	-0.0558	-0.1598	0.2068	0.5595	0.5517
	1122	18	0.3026	0.0599	0.4556	0.6669	0.5272
	749	9	0.1063	-0.1688	0.1785	0.6433	0.6478

Table A.2. Mean parameters of stand distributions of DBH

Parameter	Density	Plantation Age			
	ha^{-1}	5	6	7	8
Coefficient of Variation	6729	26.3430	23.7680	23.4704	23.2371
	4485	23.9954	21.2501	20.3088	20.8754
	3363	25.1854	22.4982	21.2655	20.5682
	2990	23.5637	20.2926	19.1856	19.2901
	2244	23.3082	20.0577	18.5880	18.2299
	1683	23.5411	19.9252	18.6212	18.1402
	1495	22.2957	18.8372	17.5705	17.0634
	1122	23.6779	19.1259	16.9675	16.0963
	749	21.5791	17.8799	15.5157	14.5682
Gini	6749	0.1587	0.1263	0.1245	0.1249
	4485	0.1449	0.1129	0.1083	0.1117
	3363	0.1570	0.1204	0.1129	0.1103
	2990	0.1384	0.1082	0.1020	0.1028
	2244	0.1402	0.1067	0.0988	0.0973
	1683	0.1431	0.1057	0.0976	0.0951
	1495	0.1341	0.1010	0.0940	0.0914
	1122	0.1414	0.1025	0.0900	0.0855
	749	0.1313	0.0955	0.0833	0.0781
Skewness	6729	-0.6049	-0.7166	-0.7484	-0.4723
	4485	-0.4584	-0.5049	-0.4767	-0.4547
	3363	-0.2680	-0.3988	-0.5034	-0.3304
	2990	-0.3297	-0.4579	-0.5390	-0.4660
	2244	-0.4111	-0.4876	-0.4786	-0.4010
	1683	-0.4769	-0.6321	-0.7957	-0.7568
	1495	-0.3054	-0.4884	-0.5164	-0.5396
	1122	-0.2787	-0.3795	-0.4712	-0.4835
	749	-0.4801	-0.6164	-0.5654	-0.5427
Kurtosis	6729	0.8198	1.1470	1.3647	0.6111
	4485	0.9038	0.9567	0.7674	0.6411
	3363	0.4316	0.6455	0.9794	0.5518
	2990	0.5381	0.6208	0.7569	0.6590
	2244	0.5977	0.8155	0.7962	0.6453
	1683	0.5988	0.9042	1.4781	1.4998
	1495	0.2799	0.6512	0.8084	0.8181
	1122	0.3529	0.6278	1.0002	1.0475
	749	0.9042	1.2338	1.0622	1.1526

Note: The numbers of observations are the same as in Table A.1.

Table A.3. Mean parameters of stand distributions of crown width

Parameter	Density	Plantation Age						
	ha^{-1}	2	3	4	5	6	7	8
Coefficient of Variation	6729	33.4464	24.5724	23.0739	19.1673	18.1212	17.8933	18.0192
	4485	34.1580	23.7630	21.1240	16.9714	16.7471	15.8378	15.4005
	3363	34.6891	24.8284	22.0360	19.6562	17.0864	14.9609	14.1277
	2990	33.1634	22.1686	20.4477	16.3455	15.5418	14.7301	13.8566
	2244	33.9467	23.9759	21.4811	18.0072	16.0669	15.1158	12.0446
	1683	33.6402	23.3058	22.3014	19.2648	16.7364	13.6179	11.6210
	1495	34.5868	24.9167	21.6489	18.0808	16.3005	15.0316	10.8550
	1122	32.7636	23.6719	21.7206	18.2909	16.3585	14.6168	10.5025
	749	31.4881	22.8330	20.9669	17.2714	16.0773	15.5277	10.0683
Gini	6729	0.1814	0.1373	0.1232	0.1011	0.0954	0.0939	0.0942
	4485	0.1869	0.1336	0.1126	0.0908	0.0889	0.0837	0.0812
	3363	0.1882	0.1403	0.1188	0.1046	0.0890	0.0776	0.0732
	2990	0.1794	0.1242	0.1108	0.0886	0.0830	0.0770	0.0705
	2244	0.1848	0.1358	0.1159	0.0968	0.0843	0.0789	0.0623
	1683	0.1826	0.1325	0.1203	0.0986	0.0884	0.0715	0.0579
	1495	0.1881	0.1395	0.1166	0.0974	0.0864	0.0797	0.0548
	1122	0.1776	0.1340	0.1178	0.0985	0.0871	0.0776	0.0533
	749	0.1713	0.1277	0.1132	0.0933	0.0863	0.0823	0.0515
Skewness	6729	-0.2313	-0.3627	-0.2738	-0.3137	-0.3718	-0.4446	-0.3332
	4485	0.0212	-0.2227	-0.2094	-0.1584	-0.2319	-0.3959	-0.4827
	3363	0.1373	-0.1299	-0.0807	-0.1217	-0.4064	-0.5849	-0.7120
	2990	0.0585	-0.1240	-0.0608	-0.0047	-0.3214	-0.6633	-1.0941
	2244	-0.0315	-0.1685	-0.0767	-0.0714	-0.3011	-0.4306	-0.4855
	1683	0.1073	-0.2372	-0.2125	0.2059	-0.3926	-0.4890	-1.0749
	1495	0.0809	-0.0627	-0.1882	-0.1888	-0.2591	-0.3122	-0.7263
	1122	0.1016	-0.0500	-0.0547	-0.0329	-0.0808	-0.3014	-0.6331
	749	-0.0397	-0.2143	-0.0111	-0.1020	0.0297	-0.3797	-0.4507
Kurtosis	6729	0.1060	0.6691	0.9047	1.5425	0.5911	1.3310	0.9574
	4485	-0.1672	0.5165	0.8676	0.8925	0.6796	0.8757	1.0884
	3363	-0.0855	0.1618	0.5779	1.0868	1.2319	1.9019	2.0103
	2990	0.1262	0.2996	0.3090	0.3032	0.2083	2.1823	2.8074
	2244	-0.1598	0.0946	0.2714	0.5187	0.9166	1.1054	1.4257
	1683	0.0745	-0.0344	0.2312	2.7661	0.3654	0.8815	3.0231
	1495	0.1186	0.5143	0.4445	0.6220	0.7256	0.5812	2.7757
	1122	0.0263	-0.0360	0.0647	0.2311	0.2479	0.6844	1.9994
	749	0.0804	0.7789	0.2892	0.4734	0.4290	1.4501	2.0588

Note: The numbers of observations are the same as in Table A.1.

Table A.4. Mean parameters of stand distributions of total height

Parameter	Density				Plantation Age				
	ha^{-1}	1	2	3	4	5	6	7	8
Coef. of Variation	6729	24.8705	25.0067	18.9793	17.3779	16.7599	14.4878	14.1748	12.7050
	4485	24.9999	23.4218	17.9455	15.8871	14.0921	12.8604	12.0790	11.4980
	3363	25.3077	24.1252	18.7999	16.7977	15.6105	13.9694	12.8411	11.5689
	2990	25.4280	23.3600	16.4159	14.9773	14.5914	12.7221	12.5085	11.3409
	2244	25.2754	23.0763	17.4850	15.2454	14.3412	12.6303	12.1451	10.5966
	1683	24.7326	22.9890	18.1762	16.4182	15.2509	13.9297	13.5011	11.7383
	1495	24.9330	24.0152	17.9761	15.9785	14.6512	13.0121	12.8811	11.5943
	1122	24.7241	23.3461	17.4661	15.6397	14.5400	12.9535	12.2375	10.9120
	749	24.5727	21.9217	16.7332	14.7189	13.5233	12.1098	11.1480	9.7610
Gini	6729	0.1382	0.1350	0.1041	0.0923	0.0875	0.0737	0.0724	0.0637
	4485	0.1398	0.1262	0.0995	0.0824	0.0738	0.0667	0.0617	0.0574
	3363	0.1394	0.1307	0.1056	0.0888	0.0815	0.0693	0.0654	0.0571
	2990	0.1444	0.1252	0.0925	0.0803	0.0783	0.0661	0.0645	0.0576
	2244	0.1399	0.1251	0.0982	0.0810	0.0758	0.0653	0.0621	0.0538
	1683	0.1357	0.1251	0.1020	0.0869	0.0794	0.0693	0.0681	0.0578
	1495	0.1390	0.1306	0.1010	0.0852	0.0773	0.0675	0.0662	0.0584
	1122	0.1356	0.1265	0.0977	0.0832	0.0771	0.0669	0.0634	0.0559
	749	0.1365	0.1191	0.0948	0.0791	0.0725	0.0642	0.0586	0.0516
Skewness	6729	0.0232	-0.2467	-0.6344	-0.7491	-1.0109	-1.1550	-1.2819	-1.4433
	4485	0.0765	-0.2531	-0.5985	-0.9642	-0.8680	-1.0367	-1.1418	-1.3323
	3363	0.3523	-0.0973	-0.3904	-0.7308	-0.8944	-1.0808	-1.1359	-1.2183
	2990	0.4740	0.0896	-0.1962	-0.3550	-0.5067	-0.7192	-1.0496	-1.2705
	2244	0.1624	-0.1663	-0.3760	-0.5251	-0.6229	-0.8139	-1.0717	-1.1379
	1683	0.0080	0.0286	-0.4198	-0.6737	-0.8761	-1.1303	-1.2591	-1.5092
	1495	0.1332	-0.2595	-0.4023	-0.4855	-0.6125	-0.7492	-0.9934	-1.2450
	1122	0.1733	-0.2255	-0.3903	-0.4399	-0.5462	-0.7782	-1.0107	-1.1385
	749	-0.0420	-0.2748	-0.4365	-0.5433	-0.6157	-0.8128	-0.9397	-0.6780
Kurtosis	6729	0.0178	0.3072	1.1687	1.3675	2.3273	2.6200	3.2799	3.9912
	4485	-0.0832	0.3159	1.2686	2.5438	1.7062	2.0659	2.6266	3.1371
	3363	0.4782	-0.0024	0.6409	1.6034	2.1499	2.9463	2.9102	3.5710
	2990	0.4238	0.6134	0.4702	0.3280	0.3979	1.2621	2.0948	3.0255
	2244	0.2618	-0.0071	0.4162	0.9033	1.1122	1.7092	2.4737	2.9775
	1683	0.2244	0.1919	0.4143	0.9594	1.5230	2.6319	2.8024	3.9408
	1495	0.0830	0.0273	0.4419	0.9444	1.0466	1.5098	2.7153	3.9445
	1122	0.3450	-0.0275	0.4940	0.8504	0.7422	1.7431	2.0882	3.1648
	749	0.2652	0.2574	0.4069	0.6047	0.8019	1.6319	2.1143	1.5427

Note: The numbers of observations are the same as in Table A.1.

Table A.5. Mean parameters of stand distributions of crown height

Parameter	Density	Plantation Age						
	ha^{-1}	2	3	4	5	6	7	8
Coefficient of Variation	6729	46.8919	36.7131	35.6397	30.5522	23.4341	18.6654	15.8816
	4485	41.7997	34.8655	37.5078	36.0442	24.1378	16.9497	16.2767
	3363	41.7078	36.3287	38.8343	39.9351	29.6965	20.3298	17.4099
	2990	43.0458	33.6739	38.5945	43.0029	29.4792	19.4394	16.8871
	2244	41.9039	36.4433	38.0603	43.6835	30.5956	21.8189	19.3083
	1683	47.6419	35.5678	39.5222	42.1085	37.4088	22.5691	20.6261
	1495	45.9746	33.1400	37.6033	41.7701	37.3173	27.9697	21.4161
	1122	44.4211	33.1429	36.3461	40.1679	40.1629	30.3083	24.2773
	749	46.1362	33.9147	38.0197	38.4017	41.5830	38.5381	28.3755
Gini	6729	0.2469	0.2008	0.1901	0.1639	0.1267	0.0995	0.0848
	4485	0.2206	0.1888	0.2001	0.1942	0.1308	0.0901	0.0863
	3363	0.2202	0.1984	0.2097	0.2130	0.1581	0.1081	0.0940
	2990	0.2313	0.1857	0.2077	0.2316	0.1591	0.1043	0.0914
	2244	0.2223	0.1960	0.2040	0.2305	0.1640	0.1160	0.1031
	1683	0.2537	0.1898	0.2135	0.2154	0.2052	0.1208	0.1103
	1495	0.2451	0.1767	0.1978	0.2143	0.2020	0.1519	0.1149
	1122	0.2358	0.1807	0.1957	0.2045	0.2173	0.1646	0.1320
	749	0.2403	0.1801	0.2032	0.1993	0.2177	0.2064	0.1558
Skewness	6729	0.4836	0.7398	0.6252	0.0618	-0.1197	-0.5422	-0.5528
	4485	0.2531	0.8076	0.7714	0.2054	-0.1275	-0.3833	-0.3718
	3363	0.4096	0.7216	0.5414	0.3671	0.0406	-0.2552	-0.1183
	2990	0.0271	0.4178	0.7189	0.5687	-0.0259	-0.2037	-0.3116
	2244	0.2655	0.8804	0.5932	0.6827	0.1546	-0.1203	0.0768
	1683	0.4210	0.7849	0.5804	0.7939	0.1134	-0.3505	-0.3937
	1495	0.1615	0.7628	0.8205	0.8616	0.2433	-0.0841	-0.1723
	1122	0.2603	0.5825	0.5693	1.0030	0.5499	0.0714	-0.0621
	303	0.4175	1.0065	0.6001	0.7698	0.8654	0.5692	-0.1666
Kurtosis	6729	0.6569	0.4973	0.7747	0.1789	-0.1290	0.9634	1.2236
	4485	0.6681	1.1291	0.7984	-0.1649	-0.0811	0.7924	1.0712
	3363	0.6335	1.1501	-0.0934	0.0023	0.4063	0.9615	0.4704
	2990	-0.0877	0.4283	0.2761	0.1187	0.2480	0.6146	0.3425
	2244	0.2526	1.4348	0.3432	0.2722	0.0846	0.6984	0.7921
	1683	0.0989	2.1067	-0.1212	1.3347	-0.5063	0.1251	0.3996
	1495	-0.0767	1.5181	0.8801	1.0009	-0.1924	-0.2852	0.6579
	1122	0.0618	1.0066	0.0263	2.1322	0.0110	-0.0407	-0.0133
	749	0.4548	2.1060	-0.0171	1.3009	0.9829	0.2546	-0.3623

Note: The numbers of observations are the same as in Table A.1.

Appendix B. Tables of Spatial Characteristics of Loblolly Pine Plantations

Table B.1. **Spatial characteristics of six year projection residuals of total height of stand growth simulators on Moran indices under the normality assumption**

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
101	39	-0.0250	0.0212	-0.0223	0.0639	0.0976	1.9638
102	38	0.0586	1.1771	0.0208	0.6578	-0.0074	0.2694
103	49	0.1836	3.2007	0.0735	1.4771	0.1298	2.3591
104	33	-0.0802	-0.8071	-0.0865	-0.9109	0.0155	0.7715
105	50	0.0084	0.4676	-0.0299	-0.1540	0.0041	0.3980
106	38	-0.0454	-0.2921	-0.0671	-0.6382	-0.0492	-0.3525
107	59	-0.0240	-0.1526	-0.0584	-0.9325	-0.0288	-0.2613
108	43	-0.0900	-0.9736	-0.0905	-0.9804	-0.0938	-1.0283
202	53	-0.0183	0.0160	-0.0343	-0.2656	0.1005	2.1151
1101	43	0.0522	1.3643	0.0376	1.1025	0.0495	1.3170
1102	44	0.0416	1.0852	-0.0076	0.2613	0.0937	1.9571
1103	43	-0.0177	0.0864	-0.0951	-1.0143	-0.0745	-0.7208
1104	58	-0.0342	-0.3232	-0.0694	-1.0054	-0.0249	-0.1417
1105	45	-0.0089	0.2556	-0.0340	-0.2087	0.0165	0.7267
1106	48	-0.0580	-0.6679	-0.0067	0.2650	0.0051	0.4799
1109	43	0.2006	3.6670	0.0268	0.8274	-0.0051	0.3052
1111	49	-0.0568	-0.6885	-0.0077	0.2517	-0.0779	-1.0923
1112	80	-0.0609	-1.1831	-0.0475	-0.8536	-0.0574	-1.0982
1113	47	0.0455	1.2385	0.0301	0.9538	-0.0015	0.3735
1114	46	0.1425	2.5616	0.0528	1.1666	-0.1147	-1.4378
1115	48	-0.0402	-0.3431	-0.0535	-0.5837	0.0168	0.6890
1116	51	0.0561	1.0455	-0.0012	0.2586	-0.0651	-0.6201
1118	90	0.0480	1.2514	0.0016	0.2710	-0.0152	-0.0842
1119	32	-0.0259	0.1116	-0.0266	0.1002	-0.0177	0.2554
1120	47	-0.0396	-0.3008	0.0009	0.3830	-0.0277	-0.1004
1122	63	-0.0579	-0.8625	-0.0187	-0.0532	-0.0044	0.2410
1123	30	0.0421	1.0128	0.0456	1.0589	0.0688	1.3662
1127	64	-0.0060	0.1967	-0.0260	-0.2012	0.0078	0.4703
1303	30	0.0271	0.9312	-0.0360	-0.0230	0.1737	3.1503
1304	29	0.0401	1.0872	-0.0082	0.3939	-0.0080	0.3974
1305	34	-0.0709	-0.4983	-0.1597	-1.5867	-0.0655	-0.4323
1307	55	-0.1006	-1.4281	-0.1158	-1.6925	-0.1041	-1.4886
1311	48	-0.0085	0.2221	0.0293	0.8806	-0.0287	-0.1293
1314	76	-0.0275	-0.3177	-0.0081	0.1176	0.0117	0.5612
1316	47	0.0421	1.0142	0.0938	1.8365	-0.0954	-1.1709
1317	49	0.0924	2.3158	0.0259	0.9555	0.0251	0.9394
1320	60	0.0005	0.3127	0.0240	0.7343	0.0193	0.6499
1321	70	0.0288	0.9947	-0.0007	0.3168	0.0039	0.4227
1324	61	-0.0747	-1.1496	-0.0988	-1.6276	-0.0758	-1.1720
1325	45	-0.0413	-0.3069	-0.0107	0.1986	-0.0708	-0.7954
1326	64	0.0151	0.6205	-0.0127	0.0639	-0.0543	-0.7708
1333	44	-0.0246	-0.0251	-0.0323	-0.1712	-0.0829	-1.1338
1336	59	-0.0815	-1.3595	-0.0740	-1.2023	-0.0261	-0.1871
1337	46	0.0764	1.7903	0.1191	2.5660	0.1005	2.2287
1341	47	-0.0738	-0.8935	-0.0708	-0.8429	-0.0631	-0.7105
1401	53	-0.0757	-1.0168	0.0086	0.5005	0.0352	0.9806

Table B.1: Continued.

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
1402	55	-0.0233	-0.0897	-0.0678	-0.9339	-0.0745	-1.0602
1404	75	0.0312	1.0624	-0.0108	0.0656	-0.0038	0.2305
1405	48	0.1685	2.2533	0.0109	0.3826	0.0878	1.2952
1406	64	-0.0396	-0.4642	0.0153	0.6108	0.0193	0.6890
1408	60	0.0019	0.3601	-0.0442	-0.5205	-0.0776	-1.1586
1409	53	0.1572	2.4528	-0.0269	-0.1061	0.0802	1.3824
1410	57	-0.0179	-0.0007	0.0783	1.5237	0.0093	0.4300
1412	77	0.0455	1.2155	0.0027	0.3278	-0.0237	-0.2178
1414	65	-0.0202	-0.0944	0.0087	0.4988	-0.0093	0.1291
1415	37	0.0839	1.4628	0.0706	1.2890	0.0948	1.6051
1416	46	-0.0046	0.3271	-0.0104	0.2204	-0.0410	-0.3485
1417	44	-0.0207	0.0417	-0.1009	-1.2504	0.0421	1.0516
2101	54	-0.1147	-1.7259	-0.1031	-1.5167	-0.0567	-0.6802
2102	51	-0.0628	-0.7402	-0.0225	-0.0428	-0.1195	-1.7206
2103	50	0.0415	1.1354	-0.0033	0.3128	-0.0521	-0.5813
2104	57	-0.0596	-0.7313	-0.0244	-0.1139	0.0121	0.5247
2105	44	0.0207	0.6744	-0.0362	-0.1981	0.0334	0.8702
2106	77	0.0134	0.5796	0.0044	0.3832	0.0106	0.5177
2107	41	-0.0383	-0.1898	-0.0231	0.0271	0.0329	0.8250
2108	51	-0.0496	-0.5324	-0.0133	0.1209	-0.0102	0.1764
2109	38	0.2005	2.3624	-0.0909	-0.6634	0.0836	1.1485
2111	49	-0.0777	-0.9859	-0.0847	-1.1059	-0.0066	0.2459
2112	50	0.0712	1.0260	-0.0310	-0.1183	0.0569	0.8659
2113	51	-0.0770	-0.9444	-0.0176	0.0405	0.0591	1.3102
2114	53	-0.0863	-1.1831	-0.0665	-0.8337	0.0943	2.0034
2115	53	0.0058	0.4422	-0.0217	-0.0427	0.0022	0.3789
2116	42	-0.0900	-1.2331	-0.0206	0.0718	-0.0525	-0.5285
2118	26	0.0367	0.8873	0.0914	1.5201	0.0826	1.4176
3101	67	-0.0215	-0.1278	-0.0304	-0.3074	-0.0679	-1.0630
3102	55	-0.0287	-0.2091	-0.0367	-0.3742	0.0187	0.7644
3103	31	-0.1389	-1.8626	-0.1499	-2.0572	-0.1053	-1.2710
3104	75	-0.0738	-1.2587	-0.0123	0.0251	-0.0403	-0.5599
3105	66	0.0374	1.1792	-0.0252	-0.2193	-0.0200	-0.1022
3108	66	-0.0167	-0.0294	-0.0184	-0.0657	-0.0221	-0.1444
3110	67	-0.0571	-0.9656	-0.0542	-0.8991	-0.0227	-0.1743
3111	54	0.0117	0.4905	-0.0213	-0.0392	0.0654	1.3529
3112	85	0.0823	1.9443	0.0195	0.6479	-0.0911	-1.6347
3113	43	-0.0845	-1.0056	-0.0656	-0.6921	-0.1179	-1.5577
3114	53	-0.0345	-0.2073	0.0212	0.5500	0.1614	2.4599
3115	41	-0.1255	-1.5227	-0.0974	-1.0972	-0.1163	-1.3826
3116	32	-0.1232	-1.1552	-0.0285	0.0482	-0.0706	-0.4874
3117	64	-0.0144	0.0298	0.0254	0.8338	-0.0352	-0.3902
3118	41	-0.0345	-0.1548	-0.0280	-0.0495	-0.0411	-0.2625
3122	40	-0.0087	0.2790	-0.0670	-0.6806	-0.0326	-0.1152
3183	42	-0.0604	-0.5972	-0.0448	-0.3384	-0.1084	-1.3922
4101	45	0.0552	0.9224	-0.0564	-0.3982	-0.0392	-0.1946

Table B.1: Continued.

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
4102	41	0.0695	1.5077	0.0564	1.2993	0.0437	1.0972
4103	39	-0.0115	0.2303	-0.0207	0.0868	-0.0371	-0.1672
4104	28	-0.1227	-1.1941	-0.1413	-1.4528	-0.1146	-1.0800
4105	68	0.0251	0.7488	-0.0455	-0.5732	-0.0446	-0.5558
4106	27	-0.0530	-0.1895	-0.1070	-0.8954	0.0401	1.0260
4107	65	0.0228	0.6233	0.0460	1.0005	0.1790	3.1600
4108	66	-0.0427	-0.4862	0.0871	1.8239	0.0005	0.2834
4109	20	-0.0257	0.3229	0.0101	0.7515	-0.0042	0.5803
4111	55	-0.0409	-0.3790	0.0185	0.6272	0.0687	1.4789
4112	38	0.0029	0.4431	0.0937	1.7892	0.0601	1.2911
4113	66	0.0886	1.6178	-0.0541	-0.6028	-0.0877	-1.1250
4114	45	-0.0392	-0.2395	0.0805	1.4996	0.0846	1.5587
4115	54	-0.0861	-1.0242	-0.1321	-1.7245	-0.0349	-0.2441
5101	52	0.0673	1.6988	-0.0095	0.1981	-0.0265	-0.1343
5104	30	-0.1068	-1.1471	-0.0658	-0.4975	-0.0923	-0.9180
5106	39	-0.0326	-0.0789	-0.0131	0.1669	-0.1109	-1.0668
5107	39	-0.0880	-0.8097	-0.0651	-0.5097	0.0253	0.6777
5108	26	-0.0085	0.5412	-0.0418	-0.0301	-0.0709	-0.5306
5109	58	-0.0160	0.0281	-0.0427	-0.4645	0.0300	0.8774
5110	36	0.1262	2.0054	-0.0206	0.1028	0.0985	1.6462
5112	46	-0.0784	-0.9534	-0.0407	-0.3131	-0.0450	-0.3868
5113	24	-0.0693	-0.4177	-0.1001	-0.9178	-0.0924	-0.7921
5114	49	0.0637	1.6284	-0.0115	0.1800	-0.0268	-0.1152
5115	45	0.0823	2.0284	-0.0333	-0.2035	-0.0701	-0.9155
6101	38	0.0258	0.7553	-0.0230	0.0572	0.0651	1.3173
6102	32	0.0660	1.2285	-0.1348	-1.2828	-0.0728	-0.5074
6103	47	-0.0058	0.2988	0.0685	1.6910	-0.0702	-0.9083
6104	53	-0.0108	0.1529	-0.0727	-0.9746	-0.0167	0.0452
6105	37	0.0270	0.7159	0.0267	0.7111	0.0264	0.7071
6106	32	0.0493	0.9700	0.0417	0.8787	-0.0574	-0.2992
6107	58	0.3097	4.8527	0.0778	1.4137	0.0576	1.1136
6109	34	-0.1010	-1.0856	-0.0709	-0.6235	-0.0120	0.2806
6112	27	-0.0498	-0.1733	-0.0460	-0.1150	0.0097	0.7369
6114	45	-0.0951	-0.9963	0.0060	0.3955	0.0982	1.6644
6116	46	0.1267	2.5824	0.0822	1.8115	0.0395	1.0709
6117	47	0.1204	1.9752	0.1499	2.3844	0.1790	2.7901
8101	29	-0.0835	-0.6683	-0.1288	-1.3006	0.0404	1.0639
8105	35	0.0682	1.6456	-0.0002	0.4928	-0.0226	0.1156
8111	52	0.1142	2.2416	0.1239	2.4042	0.1155	2.2634
8112	40	0.1034	2.2634	-0.0310	-0.0947	-0.0049	0.3637
8113	54	0.0898	2.0052	0.0820	1.8613	0.0618	1.4883
8114	67	0.0298	0.8064	0.0471	1.1184	0.0237	0.6980
8116	47	0.0773	1.7394	-0.0476	-0.4536	-0.0472	-0.4480
8121	35	-0.0493	-0.3346	-0.0800	-0.8498	-0.0283	0.0191
8122	44	-0.0336	-0.1954	-0.0290	-0.1087	0.0181	0.7820
8124	28	0.0216	0.9534	-0.0225	0.2359	-0.0134	0.3845

Table B.1: Continued.

Plot ID	N	TRULOB Moran I	TRULOB Z	PTAEDA2 Moran I	PTAEDA2 Z	PTAEDA2/APA Moran I	PTAEDA2/APA Z
8142	62	-0.0360	-0.4049	-0.0052	0.2318	-0.0088	0.1575
8155	41	-0.0839	-0.9289	-0.1107	-1.3529	-0.0787	-0.8470
9111	45	0.0754	1.7075	0.0616	1.4684	0.0569	1.3862
9131	49	0.0768	1.8307	0.0302	0.9576	0.0099	0.5762
9132	71	0.2084	4.3899	-0.0184	-0.0807	0.0083	0.4454
9134	55	0.1063	2.1978	-0.0044	0.2490	0.0543	1.2812
9136	60	0.0739	1.5792	-0.0329	-0.2777	-0.0507	-0.5870
9137	38	-0.0459	-0.2401	-0.0712	-0.5608	-0.0965	-0.8824
9141	52	-0.0419	-0.3838	-0.0632	-0.7523	-0.1056	-1.4831
9142	56	0.1505	2.8309	-0.0697	-0.8650	0.0497	1.1389
9143	80	0.1135	2.9926	0.0221	0.8235	0.0131	0.6115
9144	50	0.0966	1.8030	-0.0464	-0.4013	-0.0390	-0.2861
9171	144	0.1546	4.9165	0.0688	2.3107	0.0391	1.4092
9172	95	0.1478	3.6401	0.0452	1.2827	-0.0086	0.0477
9173	46	-0.0064	0.2593	-0.0964	-1.2162	0.0166	0.6367
9174	52	0.0318	0.8885	0.0256	0.7817	0.0577	1.3372
9175	51	0.0152	0.6180	0.0410	1.0701	0.1096	2.2735

Table B.2. Spatial characteristics of nine year projection residuals of total height of stand growth simulators on Moran indices under the normality assumption

assumption

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
1101	40	0.1488	2.9722	0.0111	0.6259	0.1299	2.6514
1102	40	0.0717	1.6773	-0.0188	0.1180	0.0586	1.4508
1103	45	0.0172	0.6779	0.0513	1.2578	-0.0111	0.1980
1111	47	0.0142	0.7107	-0.0579	-0.7135	-0.0163	0.1078
1112	69	-0.0560	-0.9848	-0.0596	-1.0718	-0.0516	-0.8805
1113	40	0.0086	0.5870	-0.0752	-0.8505	-0.0102	0.2649
1115	49	0.0870	2.0923	-0.0642	-0.8418	0.1100	2.5395
1303	30	0.0892	1.9324	0.0831	1.8366	0.1268	2.5193
1304	31	-0.0566	-0.3695	0.0444	1.2350	-0.0341	-0.0130
1305	35	0.1015	1.7600	-0.0365	-0.0954	0.1448	2.3414
1307	56	0.0144	0.6196	-0.0310	-0.2441	0.0046	0.4341
1311	46	-0.1101	-1.5669	-0.0275	-0.0939	-0.0713	-0.8755
1314	71	-0.0512	-0.8443	0.0381	1.1974	0.0128	0.6177
1325	51	-0.0639	-0.8157	-0.0306	-0.1960	-0.0209	-0.0167
1326	63	0.0254	0.8709	-0.0248	-0.1809	-0.0214	-0.1109
1341	46	-0.0265	-0.0771	-0.0679	-0.8147	-0.0719	-0.8864
1401	52	0.0094	0.5543	0.0910	2.1172	0.0305	0.9592
1402	51	-0.0088	0.2167	-0.0206	-0.0110	-0.0151	0.0950
1404	76	-0.0360	-0.5712	-0.0592	-1.1545	-0.0422	-0.7270
1405	49	0.1415	2.3082	0.0037	0.3488	0.0029	0.3380
2101	51	0.0820	1.8488	-0.0821	-1.1263	0.0857	1.9163
2102	52	-0.0492	-0.5743	-0.0282	-0.1656	-0.0509	-0.6074
2103	55	-0.0063	0.2685	0.0250	0.9592	-0.0131	0.1187
2104	55	0.0114	0.5565	-0.0102	0.1552	0.0554	1.3749
3101	67	0.0683	1.7511	0.1843	4.1846	0.0295	0.9378
3102	57	-0.0100	0.1714	0.1130	2.8603	0.0024	0.4422
3103	30	-0.0028	0.5762	-0.0363	-0.0334	-0.0145	0.3632
3110	60	-0.0573	-0.8637	0.0001	0.3643	-0.0429	-0.5559
3183	40	-0.1056	-1.3896	-0.0000	0.4452	-0.1037	-1.3564
4101	46	-0.0152	0.0922	-0.0859	-0.8389	0.0211	0.5713
4102	24	0.1024	1.7836	-0.0797	-0.4434	0.0742	1.4386
4103	25	0.0771	1.1833	-0.1560	-1.1388	0.0631	1.0440
4105	67	-0.0965	-1.5740	-0.0556	-0.7824	-0.0444	-0.5661
5101	49	0.1289	2.8958	0.0728	1.8106	0.0762	1.8765
5104	31	0.1225	2.6212	-0.0602	-0.4525	0.1161	2.5130
5113	24	0.0413	1.5038	-0.1363	-1.6478	0.0988	2.5252
6101	36	0.1073	1.9858	0.2011	3.3582	0.0889	1.7180
6102	27	-0.0781	-0.4270	-0.1506	-1.2094	-0.0950	-0.6091
6103	47	0.0427	1.2682	0.0385	1.1862	-0.0482	-0.5214
6104	50	0.0427	1.1715	-0.0242	-0.0695	-0.0474	-0.5003
8101	31	-0.0408	-0.1117	-0.1057	-1.0805	-0.0516	-0.2728
9111	39	0.2031	4.0034	0.1469	3.0214	0.1108	2.3928
9131	46	-0.0042	0.3457	-0.1003	-1.4971	-0.0321	-0.1897
9141	49	-0.0419	-0.4057	0.0396	1.1621	-0.0060	0.2860
9142	56	0.0742	1.7607	0.1124	2.4881	0.0460	1.2237

Table B.3. Spatial characteristics of six year DBH projection residuals of stand growth simulators on Moran indices under the normality assumption

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
101	39	-0.0074	0.2991	-0.0831	-0.8996	0.0318	0.9207
102	38	0.0435	0.9690	0.0313	0.8010	0.0830	1.5125
103	49	0.1785	3.1216	0.0518	1.1380	0.2502	4.2433
104	33	-0.0179	0.2200	-0.0961	-1.0691	-0.0099	0.3530
105	50	0.1263	2.3800	0.0043	0.4001	0.1594	2.9169
106	38	0.0612	1.4053	-0.0107	0.2596	0.0651	1.4666
107	59	0.0118	0.6574	-0.0463	-0.6579	0.0565	1.6689
108	43	-0.0605	-0.5386	-0.1394	-1.6997	-0.0544	-0.4491
202	53	0.0291	0.8545	0.0061	0.4467	0.0703	1.5813
1101	43	0.1105	2.4111	-0.0856	-1.1102	0.1111	2.4219
1102	44	0.1286	2.5415	0.0651	1.4782	0.2319	4.2696
1103	43	0.0879	1.5904	-0.0153	0.1208	0.0992	1.7508
1104	58	0.0003	0.3465	-0.0197	-0.0416	0.0001	0.3416
1105	45	0.1014	2.3013	-0.0389	-0.3008	0.1289	2.8118
1106	48	0.1012	2.2268	-0.0401	-0.3416	0.1343	2.8288
1109	43	0.0622	1.4059	-0.0668	-0.7034	0.0012	0.4083
1111	49	-0.0482	-0.5236	0.0055	0.5039	-0.0844	-1.2177
1112	80	-0.0200	-0.1809	-0.0576	-1.1015	-0.0314	-0.4598
1113	47	0.0962	2.1723	-0.0392	-0.3219	0.0613	1.5291
1114	46	0.0738	1.4923	-0.0072	0.2335	0.0520	1.1536
1115	48	0.0475	1.2449	-0.0564	-0.6363	0.0565	1.4078
1116	51	-0.0541	-0.4688	0.0124	0.4446	-0.0290	-0.1241
1118	90	-0.0111	0.0029	-0.0304	-0.4036	0.0230	0.7220
1119	32	0.0846	2.0545	-0.0277	0.0793	0.0651	1.7114
1120	47	-0.0202	0.0259	0.0990	2.0390	0.0181	0.6731
1122	63	-0.0185	-0.0484	-0.0157	0.0088	-0.0020	0.2910
1123	30	0.0197	0.7166	-0.0992	-0.8566	-0.0220	0.1648
1127	64	0.1188	2.6732	-0.0299	-0.2776	0.1929	4.1446
1303	30	0.1116	2.2107	0.0202	0.8267	0.2131	3.7450
1304	29	-0.0161	0.2810	0.0083	0.6309	0.0253	0.8738
1305	34	0.0218	0.6391	0.0072	0.4599	0.0926	1.5068
1307	55	0.0472	1.1425	-0.0466	-0.4879	0.0774	1.6678
1311	48	-0.1344	-1.9702	-0.0820	-1.0578	-0.0609	-0.6894
1314	76	-0.0292	-0.3550	0.0438	1.2785	0.0580	1.5975
1316	47	0.0269	0.7729	0.0810	1.6330	-0.0441	-0.3556
1317	49	0.0111	0.6542	0.0904	2.2758	-0.0432	-0.4575
1320	60	0.1447	2.8975	0.1185	2.4276	0.1179	2.4158
1321	70	0.0204	0.8014	-0.0155	-0.0238	-0.0100	0.1025
1324	61	0.0048	0.4248	0.0067	0.4635	0.0263	0.8504
1325	45	0.0182	0.6765	0.0860	1.7995	0.0332	0.9253
1326	64	-0.0038	0.2417	-0.0359	-0.4018	-0.0038	0.2421
1333	44	-0.0101	0.2498	0.0818	1.9992	-0.0248	-0.0291
1336	59	-0.0255	-0.1748	-0.0346	-0.3683	-0.0365	-0.4085
1337	46	0.0722	1.7135	0.0641	1.5672	0.0977	2.1782
1341	47	-0.0363	-0.2497	-0.0594	-0.6464	-0.0577	-0.6177
1401	53	0.0939	2.0372	-0.0220	-0.0492	0.0403	1.0727

Table B.3: Continued.

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
1402	55	0.0123	0.5845	-0.0522	-0.6389	0.0287	0.8946
1404	75	-0.0258	-0.2910	0.0702	1.9894	0.0084	0.5197
1405	48	0.0848	1.2598	0.0831	1.2390	0.1564	2.1105
1406	64	0.0567	1.4200	-0.0219	-0.1185	0.0282	0.8619
1408	60	0.0212	0.7273	0.0616	1.4998	0.0320	0.9335
1409	53	0.0748	1.3072	0.0203	0.5503	0.0333	0.7301
1410	57	0.1397	2.4973	-0.0207	-0.0456	0.1721	3.0115
1412	77	-0.0711	-1.2004	0.0038	0.3507	-0.0609	-0.9884
1414	65	0.0171	0.6694	0.0172	0.6725	0.0813	1.9852
1415	37	0.0040	0.4168	0.0390	0.8740	0.0541	1.0718
1416	46	0.2547	5.1516	0.0655	1.6313	0.2582	5.2164
1417	44	-0.0377	-0.2323	-0.0610	-0.6074	0.0131	0.5860
2101	54	0.0580	1.3845	-0.0169	0.0362	0.0860	1.8884
2102	51	-0.0882	-1.1794	0.0576	1.3414	-0.0742	-0.9375
2103	50	-0.0524	-0.5860	-0.0376	-0.3146	-0.0103	0.1857
2104	57	0.0541	1.2598	-0.0210	-0.0558	0.0758	1.6413
2105	44	0.0698	1.4291	-0.0752	-0.7983	0.0384	0.9461
2106	77	0.0278	0.8941	0.0201	0.7262	0.0330	1.0068
2107	41	0.0519	1.0955	0.0425	0.9614	0.0597	1.2059
2108	51	0.0133	0.5984	0.0177	0.6774	0.0491	1.2440
2109	38	-0.1111	-0.8727	0.0694	1.0015	-0.0304	-0.0345
2111	49	0.0538	1.2932	0.0005	0.3695	0.1148	2.3511
2112	50	0.1051	1.4053	0.0358	0.6300	0.2355	2.8659
2113	51	-0.0540	-0.5633	0.0229	0.7112	-0.0011	0.3128
2114	53	-0.1204	-1.7860	-0.0458	-0.4695	-0.0583	-0.6900
2115	53	0.1339	2.7023	0.1275	2.5898	0.1312	2.6555
2116	42	0.0156	0.7507	0.0407	1.2229	0.0198	0.8307
2118	26	0.0110	0.5901	-0.0122	0.3212	0.1071	1.7013
3101	67	0.0402	1.1148	0.1880	4.0924	0.0367	1.0438
3102	55	0.0797	2.0199	0.0574	1.5613	0.1057	2.5546
3103	31	-0.0169	0.2894	-0.0717	-0.6770	-0.0111	0.3921
3104	75	0.1588	3.5948	0.1277	2.9472	0.2220	4.9131
3105	66	-0.0439	-0.6372	-0.0147	0.0148	-0.0260	-0.2362
3108	66	-0.0307	-0.3305	0.0208	0.7832	0.0031	0.3993
3110	67	-0.0438	-0.6611	0.0173	0.7483	0.0063	0.4949
3111	54	-0.0354	-0.2661	-0.0548	-0.5767	0.0247	0.6992
3112	85	0.1578	3.5018	0.1401	3.1354	0.1484	3.3071
3113	43	0.0023	0.4324	0.0663	1.4922	0.0809	1.7338
3114	53	0.2239	3.3114	0.2033	3.0304	0.4299	6.1169
3115	41	0.0131	0.5768	0.0440	1.0457	-0.0314	-0.0964
3116	32	-0.0048	0.3488	-0.0744	-0.5358	0.0135	0.5817
3117	64	0.1340	3.0245	0.0407	1.1423	0.1504	3.3556
3118	41	-0.0669	-0.6827	-0.0050	0.3263	-0.0391	-0.2293
3122	40	-0.0400	-0.2367	0.1030	2.1168	-0.0722	-0.7667
3183	42	-0.0804	-0.9284	0.0058	0.5008	-0.0855	-1.0127
4101	45	0.1599	2.1631	0.1057	1.5211	0.2027	2.6703

Table B.3: Continued.

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
4102	41	0.2555	4.4771	-0.0504	-0.4048	0.2586	4.5262
4103	39	-0.0581	-0.4934	-0.0456	-0.2995	-0.0427	-0.2534
4104	28	0.1030	1.9513	-0.0044	0.4547	0.0773	1.5926
4105	68	-0.0574	-0.7951	-0.0543	-0.7378	0.0185	0.6250
4106	27	0.0118	0.6562	-0.0942	-0.7281	0.0806	1.5556
4107	65	0.0933	1.7676	0.0501	1.0676	0.1760	3.1108
4108	66	0.1955	3.7544	0.0328	0.8588	0.2159	4.1181
4109	20	-0.0634	-0.1285	-0.0487	0.0467	-0.0412	0.1370
4111	55	-0.0253	-0.1153	0.1043	2.0816	0.0127	0.5291
4112	38	0.0960	1.8223	0.2231	3.7051	0.1530	2.6668
4113	66	0.2616	4.3081	0.1173	2.0638	0.3367	5.4768
4114	45	0.0142	0.5367	-0.0515	-0.4179	0.0410	0.9264
4115	54	0.0545	1.1164	-0.0790	-0.9157	0.1230	2.1606
5101	52	0.0871	2.0845	0.0900	2.1413	0.0763	1.8733
5104	30	0.0113	0.7270	-0.0565	-0.3499	0.0865	1.9202
5106	39	0.0388	0.8214	0.0153	0.5254	0.0236	0.6290
5107	39	0.0403	0.8745	-0.0732	-0.6157	0.2016	2.9916
5108	26	-0.0613	-0.3652	-0.0807	-0.6977	-0.1035	-1.0901
5109	58	0.0972	2.1169	-0.0500	-0.5991	0.1857	3.7503
5110	36	0.0865	1.4901	-0.0738	-0.5864	0.1830	2.7408
5112	46	0.0669	1.5122	-0.0090	0.2251	-0.0258	-0.0613
5113	24	0.0447	1.4278	-0.0794	-0.5818	0.0363	1.2925
5114	49	0.1881	4.0244	-0.0497	-0.5560	0.2073	4.3945
5115	45	0.0307	1.0318	-0.0924	-1.3455	0.0763	1.9119
6101	38	-0.0009	0.3736	0.1268	2.1998	0.0524	1.1354
6102	32	-0.1396	-1.3425	-0.0679	-0.4460	-0.1235	-1.1416
6103	47	0.0216	0.8131	0.0864	2.0263	0.0256	0.8879
6104	53	0.1071	2.3022	-0.0526	-0.6081	-0.0082	0.2015
6105	37	-0.0714	-0.5694	-0.0680	-0.5252	-0.0790	-0.6683
6106	32	-0.0463	-0.1675	-0.1050	-0.8647	-0.0604	-0.3345
6107	58	-0.0065	0.1636	-0.0557	-0.5665	0.1534	2.5355
6109	34	-0.0666	-0.5566	0.0194	0.7622	0.0382	1.0508
6112	27	0.2358	4.1994	0.0102	0.7449	0.2585	4.5466
6114	45	0.1726	2.6888	0.0592	1.1277	0.2866	4.2585
6116	46	0.0952	2.0368	0.0139	0.6263	0.1316	2.6677
6117	47	0.1051	1.7627	0.0778	1.3835	0.1313	2.1261
8101	29	0.0477	1.1659	-0.0559	-0.2820	0.0390	1.0439
8105	35	0.0589	1.4892	0.0819	1.8775	0.0501	1.3404
8111	52	0.1154	2.2619	0.0790	1.6517	0.1850	3.4278
8112	40	0.0625	1.5461	0.0022	0.4880	0.0893	2.0166
8113	54	0.0000	0.3489	-0.0259	-0.1291	0.0151	0.6261
8114	67	0.0663	1.4631	0.0081	0.4180	0.0939	1.9572
8116	47	0.2000	3.8943	0.0279	0.8723	0.0513	1.2828
8121	35	0.0036	0.5535	-0.0742	-0.7520	-0.0065	0.3854
8122	44	-0.0244	-0.0226	0.0216	0.8488	-0.0674	-0.8349
8124	28	-0.0282	0.1439	0.1005	2.2382	0.0087	0.7439

Table B.3: Continued.

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
8142	62	-0.0317	-0.3160	0.1024	2.4540	-0.0227	-0.1297
8155	41	0.0115	0.5765	0.0908	1.8283	-0.0246	0.0060
9111	41	0.2100	3.6978	0.2630	4.5314	0.1446	2.6684
9131	49	0.0148	0.6687	-0.0201	0.0146	0.0112	0.6007
9132	71	-0.0257	-0.2251	-0.0459	-0.6231	0.1802	3.8330
9134	55	0.0962	2.0184	-0.0305	-0.2110	0.0826	1.7793
9136	60	0.0902	1.8621	-0.0164	0.0104	0.0889	1.8399
9137	38	-0.1292	-1.2975	-0.0410	-0.1773	0.0302	0.7271
9141	52	0.0720	1.5805	0.1165	2.3479	0.0880	1.8554
9142	56	0.0056	0.3987	-0.0141	0.0677	-0.0408	-0.3792
9143	80	0.1086	2.8753	0.0079	0.4887	0.1022	2.7256
9144	50	0.0172	0.5801	-0.0051	0.2356	0.0303	0.7818
9171	144	0.0621	2.1061	0.0066	0.4221	0.0922	3.0206
9172	95	-0.0053	0.1222	-0.0289	-0.4192	0.0937	2.3976
9173	46	0.0403	1.0244	0.0054	0.4525	0.0375	0.9788
9174	52	-0.0514	-0.5498	-0.0253	-0.0989	-0.0274	-0.1354
9175	51	0.0716	1.6063	0.0721	1.6156	0.1194	2.4450

Table B.4. **Spatial characteristics of nine year DBH projection residuals of stand growth simulators on Moran indices under the normality assumption**

		TRULOB		PTAEDA2		PTAEDA2/APA	
Plot ID	N	Moran I	Z	Moran I	Z	Moran I	Z
1101	40	0.0430	1.1702	-0.0162	0.1608	0.0555	1.3835
1102	40	0.0020	0.4762	-0.0587	-0.5689	0.0057	0.5398
1103	45	0.0316	0.9222	-0.0531	-0.5165	-0.0440	-0.3608
1111	47	-0.0780	-1.1121	-0.0848	-1.2463	-0.0923	-1.3932
1112	69	-0.0638	-1.1727	-0.0248	-0.2399	-0.0708	-1.3399
1113	40	-0.0059	0.3383	-0.0335	-0.1351	-0.0303	-0.0795
1115	49	-0.0584	-0.7291	-0.0393	-0.3593	0.0263	0.9141
1303	30	-0.0596	-0.3929	0.0032	0.5879	0.0357	1.0958
1304	31	-0.0293	0.0633	-0.0413	-0.1270	-0.0386	-0.0835
1305	35	-0.0346	-0.0702	-0.1373	-1.4495	-0.1074	-1.0485
1307	56	-0.0738	-1.0588	-0.0699	-0.9842	-0.0993	-1.5442
1311	46	-0.0326	-0.1845	-0.0160	0.1102	-0.0418	-0.3485
1314	71	-0.0624	-1.0982	-0.0547	-0.9237	-0.0056	0.1979
1325	51	-0.0567	-0.6814	-0.0582	-0.7093	-0.0688	-0.9063
1326	63	-0.0443	-0.5908	-0.0850	-1.4438	-0.0947	-1.6471
1341	46	-0.0658	-0.7764	-0.0741	-0.9247	-0.0455	-0.4153
1401	52	-0.0157	0.0745	0.0444	1.2246	0.0291	0.9327
1402	51	0.0021	0.4287	0.0059	0.5023	-0.0528	-0.6355
1404	76	0.0521	1.6480	-0.0656	-1.3159	-0.0232	-0.2481
1405	49	0.1638	2.6251	-0.0088	0.1708	0.0744	1.3533
2101	51	-0.0701	-0.9078	-0.0770	-1.0333	-0.0416	-0.3921
2102	52	-0.0389	-0.3737	-0.0512	-0.6117	-0.0855	-1.2771
2103	55	0.0464	1.4311	-0.0335	-0.3296	-0.0502	-0.6980
2104	55	-0.0705	-0.9658	-0.0507	-0.5983	0.0386	1.0614
3101	67	-0.0266	-0.2412	-0.0666	-1.0786	-0.0677	-1.1026
3102	57	-0.0557	-0.8265	-0.0419	-0.5251	-0.0057	0.2657
3103	30	-0.0838	-0.8987	-0.0465	-0.2189	-0.0463	-0.2158
3110	60	-0.0453	-0.6054	0.0052	0.4745	-0.0213	-0.0927
3183	40	-0.0926	-1.1632	-0.0361	-0.1814	-0.1231	-1.6941
4101	46	0.0204	0.5622	-0.0579	-0.4706	-0.0537	-0.4154
4102	24	-0.1064	-0.7694	-0.1415	-1.1983	-0.1045	-0.7465
4103	25	-0.1072	-0.6535	-0.0892	-0.4734	0.0104	0.5189
4105	67	0.0692	1.6331	-0.0336	-0.3571	-0.0737	-1.1332
5101	49	0.0363	1.1055	0.0125	0.6452	-0.0449	-0.4649
5104	31	-0.0602	-0.4516	-0.0662	-0.5525	-0.0450	-0.1955
5113	24	-0.0748	-0.5563	-0.0588	-0.2724	-0.0813	-0.6710
6101	36	0.0273	0.8172	-0.0077	0.3058	0.0660	1.3826
6102	27	0.0076	0.4971	-0.1680	-1.3966	-0.1222	-0.9034
6103	47	-0.0131	0.1693	0.0608	1.6246	-0.0756	-1.0596
6104	50	-0.0306	-0.1889	-0.0555	-0.6522	-0.0594	-0.7248
8101	31	-0.0483	-0.2235	-0.0761	-0.6386	-0.0195	0.2068
9111	39	0.0449	1.2431	0.0859	1.9586	0.0446	1.2373
9131	46	0.0358	1.1120	-0.0017	0.3931	-0.0167	0.1055
9141	49	-0.0334	-0.2406	-0.0817	-1.1694	-0.0881	-1.2917
9142	56	0.1016	2.2827	-0.0309	-0.2414	-0.0182	0.0003

Table B.5. Spatial autocorrelation tests of increment of DBH and total height over nine year period on Moran indices under the normality assumption

		HEIGHT		DBH	
Plot ID	N	Moran I	Z	Moran I	Z
101	46	0.0213	0.7003	0.1169	2.2367
102	41	0.0153	0.5718	-0.0167	0.1185
103	49	0.0194	0.6307	-0.0022	0.2922
104	38	-0.0333	-0.1071	0.0313	0.9996
105	56	-0.0129	0.0888	-0.0496	-0.5261
106	43	0.0211	0.7356	-0.0632	-0.6462
107	75	0.0191	0.7973	0.0034	0.4130
108	46	-0.0876	-1.0011	-0.0914	-1.0585
202	54	0.0611	1.4213	-0.0235	-0.0827
1101	46	-0.0559	-0.6146	0.0854	1.9668
1102	49	0.1274	2.5406	-0.0021	0.3215
1103	44	0.0391	0.8919	-0.1136	-1.2938
1104	59	-0.0146	0.0526	-0.0184	-0.0231
1105	52	0.0127	0.6296	-0.0282	-0.1681
1106	49	0.0542	1.3693	0.0805	1.8492
1109	45	-0.0193	0.0567	-0.0433	-0.3442
1111	50	-0.0621	-0.8049	-0.0601	-0.7660
1112	89	-0.0127	-0.0335	-0.0570	-1.1790
1113	50	0.0250	0.8618	0.0166	0.7020
1114	46	0.0376	0.9301	0.0597	1.2738
1115	49	0.0753	1.7482	-0.0409	-0.3657
1116	55	0.0312	0.7076	-0.0145	0.0579
1118	97	-0.0390	-0.6263	-0.0266	-0.3541
1119	37	-0.0420	-0.2594	-0.0192	0.1568
1120	49	0.0784	1.6993	-0.0669	-0.7894
1122	73	0.1188	2.9202	-0.0391	-0.5548
1123	42	-0.0890	-0.9355	0.0426	0.9705
1127	67	-0.0544	-0.7888	-0.0762	-1.2267
1303	30	0.0955	1.9668	-0.0016	0.4982
1304	34	0.0066	0.5482	-0.0751	-0.6657
1305	34	0.2254	3.1359	0.0617	1.1287
1307	55	-0.0287	-0.1774	-0.0115	0.1222
1311	51	-0.0993	-1.4095	0.0070	0.4806
1314	80	0.0634	1.7452	-0.0179	-0.1199
1316	50	0.0721	1.5222	-0.0522	-0.5238
1317	52	0.0599	1.6706	0.0036	0.4873
1320	64	0.1193	2.5243	0.0039	0.3697
1321	70	0.0622	1.7616	0.0770	2.0999
1324	70	-0.0097	0.1006	-0.0991	-1.7744
1325	54	0.0296	0.8623	-0.0623	-0.7719
1326	70	-0.0601	-0.9381	-0.0226	-0.1666
1333	48	0.0268	0.9454	-0.0485	-0.5347
1336	61	-0.0659	-1.0680	-0.0446	-0.6069
1337	52	0.0409	1.1180	0.0725	1.7015
1341	51	-0.0661	-0.8205	-0.0237	-0.0658
1401	55	0.1078	2.3175	-0.0610	-0.7795

Table B.5: Continued.

		HEIGHT		DBH	
Plot ID	N	Moran I	Z	Moran I	Z
1402	56	-0.0202	-0.0384	-0.0622	-0.8496
1404	76	0.0105	0.5718	-0.0015	0.2846
1405	48	0.2874	3.6662	0.0369	0.6910
1406	69	0.0161	0.6231	-0.0543	-0.7994
1408	62	0.0230	0.7579	-0.1126	-1.8506
1409	53	0.2144	3.2494	-0.0007	0.2581
1410	60	0.0184	0.5726	0.0850	1.6532
1412	77	0.0497	1.3015	0.0116	0.5126
1414	66	0.0166	0.6601	-0.0351	-0.4071
1415	41	-0.0770	-0.7060	0.0651	1.2230
1416	49	0.1147	2.5835	-0.0380	-0.3269
1417	45	-0.0330	-0.1659	-0.0188	0.0641
2101	57	0.0622	1.4812	-0.0894	-1.3242
2102	51	0.0218	0.7222	-0.0589	-0.6727
2103	51	0.0812	1.8582	0.0215	0.7613
2104	60	0.0106	0.4922	-0.0408	-0.4262
2105	53	-0.0492	-0.4971	0.0119	0.5173
2106	79	0.0147	0.6073	-0.0212	-0.1844
2107	41	0.0849	1.5647	-0.0102	0.2105
2108	58	0.0066	0.4591	-0.0917	-1.4087
2109	39	-0.0537	-0.2866	0.1003	1.3249
2111	51	0.1047	2.1778	-0.0388	-0.3277
2112	52	0.1152	1.5512	-0.0652	-0.5252
2113	52	-0.0288	-0.1530	-0.0979	-1.2997
2114	64	0.0026	0.3503	-0.0577	-0.7956
2115	57	0.0981	2.1101	-0.0489	-0.5657
2116	45	-0.0167	0.1143	-0.0717	-0.9372
2118	26	0.0231	0.7302	0.0715	1.2889
3101	71	0.2251	4.9276	-0.0358	-0.4429
3102	56	0.0094	0.5738	-0.0227	-0.0942
3103	33	-0.0936	-1.1068	-0.1273	-1.7062
3104	83	0.1125	2.7440	-0.0825	-1.5485
3105	67	0.0150	0.6768	-0.0279	-0.2856
3108	73	0.0213	0.7974	-0.0132	0.0156
3110	71	0.0881	2.4106	-0.0508	-0.8608
3111	68	-0.0437	-0.5153	0.0140	0.5169
3112	93	0.0918	2.2262	-0.0294	-0.4012
3113	53	0.0652	1.5305	-0.0863	-1.2155
3114	57	0.2909	4.2751	-0.0080	0.1364
3115	42	-0.0415	-0.2610	-0.1166	-1.4087
3116	34	-0.0703	-0.5177	-0.0934	-0.8165
3117	81	0.0240	0.8104	-0.0382	-0.5691
3118	45	0.0195	0.7164	-0.0022	0.3480
3122	41	0.1179	2.3728	-0.0188	0.1029
3183	47	-0.0413	-0.3434	-0.0608	-0.6843
4101	47	0.1549	2.1316	-0.0052	0.1994

Table B.5: Continued.

		HEIGHT		DBH	
Plot ID	N	Moran I	Z	Moran I	Z
4102	53	-0.0190	0.0043	0.0641	1.4550
4103	49	-0.0454	-0.4192	-0.0673	-0.7933
4104	29	0.0350	0.9909	-0.1323	-1.3532
4105	70	-0.0488	-0.6515	-0.0505	-0.6839
4106	34	-0.0309	-0.0081	-0.0556	-0.3611
4107	70	0.0429	0.9697	-0.0201	-0.0942
4108	73	-0.0070	0.1292	0.0114	0.4759
4109	30	-0.1000	-0.8586	-0.0165	0.2357
4111	59	0.0097	0.4656	-0.0361	-0.3256
4112	44	0.0713	1.4706	-0.0153	0.1238
4113	67	0.1079	1.9332	0.0468	0.9728
4114	54	0.0295	0.7569	0.0330	0.8115
4115	67	-0.0306	-0.2633	-0.1051	-1.5289
5101	56	0.1508	3.3951	0.0272	0.9118
5104	35	-0.1245	-1.5693	-0.0949	-1.0797
5106	46	0.0097	0.4372	-0.0763	-0.7399
5107	40	-0.0664	-0.5450	-0.0657	-0.5356
5108	28	-0.0526	-0.2656	-0.0452	-0.1394
5109	59	-0.0472	-0.5553	-0.0890	-1.3298
5110	38	0.0630	1.1731	-0.0015	0.3328
5112	47	-0.0378	-0.2744	-0.0806	-1.0064
5113	30	-0.0378	-0.0561	-0.0663	-0.5448
5114	49	-0.0207	0.0033	-0.0323	-0.2210
5115	52	-0.0726	-1.0681	-0.0596	-0.8057
6101	41	0.0522	1.1314	-0.0294	-0.0640
6102	37	-0.0672	-0.5222	0.0064	0.4530
6103	50	-0.0141	0.1227	-0.0393	-0.3642
6104	56	0.0416	1.1069	-0.0461	-0.5178
6105	39	-0.0180	0.1108	0.0448	0.9478
6106	33	-0.0920	-0.7317	-0.0986	-0.8109
6107	59	0.0052	0.3338	0.0562	1.0937
6109	34	0.1269	2.4133	-0.1216	-1.4016
6112	31	0.1032	2.0850	-0.0599	-0.4060
6114	46	0.1763	2.7560	-0.0333	-0.1531
6116	46	0.0357	1.0050	0.0335	0.9669
6117	49	0.0764	1.3748	0.0129	0.4772
8101	31	0.0450	1.0961	-0.0230	0.1445
8105	41	0.0866	2.0009	-0.0655	-0.7265
8111	52	0.0293	0.8193	-0.0059	0.2291
8112	41	0.0670	1.6162	0.0785	1.8171
8113	58	-0.0428	-0.4785	-0.0002	0.3286
8114	67	0.0181	0.5972	-0.0082	0.1256
8116	55	0.1214	2.5998	-0.0283	-0.1824
8121	35	-0.0043	0.4214	-0.0922	-1.0541
8122	47	-0.0350	-0.2528	-0.0612	-0.7517
8124	29	0.0178	0.8712	-0.0156	0.3277

Table B.5: Continued.

		HEIGHT		DBH	
Plot ID	N	Moran I	Z	Moran I	Z
8142	64	0.1048	2.5103	-0.0178	-0.0394
8155	46	0.0879	1.8477	-0.0844	-1.0431
9111	46	-0.0856	-1.1038	0.0997	2.1237
9131	49	0.0637	1.5846	0.0654	1.6178
9132	74	-0.0349	-0.4251	0.0237	0.7475
9134	56	0.0565	1.3196	0.0579	1.3442
9136	61	0.0020	0.3251	-0.0454	-0.5007
9137	38	-0.0793	-0.6632	-0.0173	0.1236
9141	52	0.0630	1.4248	-0.0047	0.2579
9142	56	0.1930	3.5434	-0.0138	0.0728
9143	80	0.0393	1.2325	0.0845	2.3051
9144	50	0.0269	0.7296	-0.0410	-0.3181
9171	144	0.0451	1.6126	0.0084	0.4749
9172	97	-0.0294	-0.4396	-0.0289	-0.4290
9173	47	0.0842	1.7549	-0.0260	-0.0708
9174	52	-0.0033	0.2823	0.0116	0.5397
9175	51	0.0593	1.3915	0.0160	0.6313

Table B.6. **Spatial autocorrelation tests of increment of DBH and total height over nine year period on Moran indices under the normality assumption**

		HEIGHT		DBH	
Plot ID	N	Moran I	Z	Moran I	Z
1101	51	0.0771	1.8304	0.0777	1.8409
1102	57	0.0432	1.1409	-0.0581	-0.7522
1103	47	0.0300	0.8904	-0.0653	-0.7494
1111	58	-0.0289	-0.2410	-0.0854	-1.4397
1112	93	-0.0669	-1.4954	-0.0742	-1.6902
1113	52	0.0135	0.6151	0.0016	0.3951
1115	51	0.0178	0.7456	-0.0382	-0.3589
1303	32	-0.0382	-0.0938	-0.0170	0.2390
1304	39	-0.0078	0.3030	-0.0656	-0.6420
1305	36	-0.0336	-0.0680	-0.0010	0.3755
1307	57	-0.0366	-0.3575	-0.0492	-0.5975
1311	53	-0.0713	-0.9655	-0.0168	0.0449
1314	86	0.0452	1.4074	-0.0545	-1.0554
1325	69	-0.0561	-0.8766	-0.0611	-0.9820
1326	76	0.0196	0.7343	-0.0483	-0.7782
1341	60	-0.0704	-1.0563	-0.0229	-0.1181
1401	64	-0.0328	-0.3503	-0.0593	-0.9002
1402	61	-0.0533	-0.7606	-0.0262	-0.1976
1404	81	0.0394	1.3444	0.0507	1.6369
1405	49	0.1097	1.8562	0.0309	0.7349
2101	59	0.0356	1.0233	-0.0682	-0.9865
2102	54	-0.0391	-0.3981	-0.0439	-0.4915
2103	56	0.1054	2.7238	0.0400	1.2825
2104	59	0.0031	0.3893	-0.0228	-0.1069
3101	73	0.2462	5.6461	-0.0507	-0.7983
3102	60	0.0344	1.1481	-0.0533	-0.8125
3103	44	-0.0901	-1.2956	-0.0914	-1.3215
3110	75	0.0208	0.8032	-0.0501	-0.8568
3183	50	-0.0562	-0.6847	-0.1081	-1.6745
4101	49	-0.0731	-0.7128	-0.0703	-0.6745
4102	71	-0.0670	-0.9486	-0.0997	-1.5350
4103	52	0.0072	0.3731	-0.0679	-0.6722
4105	74	-0.0623	-0.9849	-0.0780	-1.3028
5101	58	0.1199	2.8633	0.0029	0.4266
5104	41	-0.0833	-1.0661	-0.0471	-0.4038
5113	34	-0.0369	-0.1173	-0.0818	-0.9095
6101	41	0.1504	2.6651	-0.0499	-0.3779
6102	41	-0.0848	-0.7577	-0.1134	-1.1194
6103	56	-0.0546	-0.7746	-0.0516	-0.7115
6104	63	-0.0256	-0.1910	-0.0697	-1.0793
8101	44	-0.0639	-0.6808	-0.0605	-0.6240
9111	46	0.0439	1.2047	0.0690	1.6623
9131	48	-0.0322	-0.2142	0.0404	1.2095
9141	51	0.0381	1.1193	-0.0320	-0.2320
9142	56	0.1901	3.9680	-0.0591	-0.7798

Vita

The Author was born in Rugou, Jiangsu, the People's Republic of China on July 25, 1960. He commenced his education with public school system and graduated from Changnan High School in Jiangsu, China in 1977. In 1978, he entered Nanjing Forestry University as a forestry major obtaining a Bachelor of Science degree in forestry in 1982 and a Master of Science degree in forest ecology in 1985.

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