ABSTRACT

COULSTON, JOHN WESLEY. Simulating Forest Stands By Resampling One-Acre Stem Maps: Spatial Characteristics of Results. (Under the direction of Carlyle Franklin.)

The purpose of this research is to generate forest stands for sampling simulations on an operational level. In this research, a simulated forest stand consists of *x* and *y* coordinates of stems and their attributes. One-acre stem maps are mapped stem locations and attributes from the field. The simulation procedure is a two step process. The first step is to create discrete samples from a one-acre stem map. Secondly, the discrete samples are selected randomly with replacement and placed adjacently until a simulated forest stand of desired size and shape is built. The simulated forest stands are then compared with the one-acre stem map from which they were created by their respective average clump size, spatial point pattern, and spatial variability of stem diameter. Average clump size is estimated using stem counts from grids of contiguous quadrats (Greig-Smith, 1952). Spatial point pattern is classified based on the mean and variance of first, second, third, and fourth nearest neighbor distances (Smith, 1977). The spatial variability of stem diameter is assessed using the robust semi-variogram estimator (Cressie *et al.*, 1980) The ability of the simulation procedure to reproduce the above mentioned spatial characteristics is related to the second order stationarity of stem diameter in the one-acre stem map. In this case, second order stationarity is the premise that the mean stem diameter is constant in the one-acre stem map and the variance is only dependant on stem separation distance. Stem locations, the species percentages, and the coefficient of variation of stem diameter should be assessed to determine the applicability of this simulation procedure for a particular one-acre stem map.

SIMULATING FOREST STANDS BY RESAMPLING ONE-ACRE STEM MAPS: SPATIAL CHARACTERISTICS OF RESULTS

by

JOHN WESLEY COULSTON

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BIOGRAPHY

John Wesley Coulston was born February 6, 1973 to Jacqueline Wright Coulston and the late John Michael Coulston. The author was introduced to forestry at Tatum Tree Farm where he worked managing Christmas trees and timber throughout his high school years. In 1991, the author graduated from Davie County High School located in Mocksville, North Carolina. His education continued at North Carolina State University in the Forest Management curriculum. As an undergraduate, the author was a member of the varsity wrestling squad. He received the degree of Bachelor of Science in Forest Management in the spring of 1996 then enrolled in the Master of Science program in the fall of 1996.

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1. INTRODUCTION

A forest stand is a spatially continuous group of trees and associated vegetation with similar species composition, age structure, canopy structure, growing under the same soil condition and climatic situation (McGaughey, 1996). Forest stands are the basic unit in forest management. Simulated forest stands are important when assessing forest inventory methods, sampling techniques, and many other spatially dependant aspects of forestry because stem mapping entire stands is not feasible. Simulated forest stands and stem maps consist of stem coordinates, and stem attributes. They often have information about stand age, physiographic zone, slope, aspect, vegetative cover, soil, and other variables in the area (APA, 1969). The variables recorded and the range of tree sizes measured varies and is dependant on the goals of the mapper. The largest stem map, represents a 10 acre forested area near Syracuse New York (Netto, 1967). While Netto's stem map is an extraordinary data set, it is still of marginal size to use for cruising simulations and only represents one forest stand type. One-acre stem maps are much more common. For example, Virginia Polytechnic Institute and State University has a stem map library composed of 93 different stem maps, most of which are one-acre (Reed and Burkhart, 1985). The American Pulpwood Association (1969) labeled one-acre stem maps "forest models" because they are representations of the spatial arrangement of stems and spatial variation of stem attributes of a particular forest stand. Many procedures for simulating forest stands, based on stem maps and other empirical methods, have been developed to study a variety of forestry practices.

Newnham (1964) developed one of the first methods of simulating forest stands. This method was based on allocating mortality to evenly spaced stems to make a realistic spatial pattern of stems. He later developed clumped stands by creating a grid of rectangular cells and determining the number of trees per rectangle by random selection from the negative binomial distribution (Newnham, 1966).

The purpose of Newnham's (1966) study was to assess the impact of stand structure and mechanical harvester size on harvesting pattern. Others developed methods to simulate forest stands for different reasons. Palley *et al.* (1961) simulated forest stands to compare Bitterlich's point sampling method and Strand's line sampling method. Kaltenberg (1978) and Hann *et al.* (1991) also used simulated forest stands to evaluate alternative sampling schemes. Mitchell (1969) and Daniels *et al.* (1979) used simulated forest stand maps in developing distance-dependant growth and yield models. Hanus *et al.* (1998) used a nonsimple sequential inhibition process to generate coordinates for displaying forest stand structure in young naturally regenerated Douglas-fir stands.

Hanus *et al.* (1998) identified six processes used to simulate forest stands. The processes were: the Poisson forest, Poisson cluster process, doubly stochastic Poisson process, lattice process, inhibition and Markov process, and nonsimple sequential inhibition process. The Poisson forest, Poisson cluster process, doubly stochastic Poisson process and lattice process all assigned stem coordinates by one algorithm and stem attributes by another algorithm (Hanus *et al.*, 1998). The inhibition and Markov process and nonsimple sequential inhibition process assigned stem coordinates based on stem attributes. Of the six processes Hanus *et al.* identified, the Markov and nonsimple sequential inhibition processes were the most realistic forest stand simulators because they mimicked competition by forcing small trees to be placed next to large trees.

The processes that Hanus *et al.* (1998) described attempted to simulate forest stands that have real world spatial characteristics such as average clump size, spatial point pattern, and spatial variation of stem attributes. Several researchers have used and developed tools to assess and describe average clump size, spatial point patterns, and spatial variations of stem attributes.

Greig-Smith (1952) used grids of contiguous quadrats to assess average clump size in ecological sampling. This method used a nested analysis of variance on the number of observations that fell within and between different quadrats . Phillips (1954) used Greig-Smith's method to quantify the competition and dispersion of *Eriophorum angustifolium* (cotton grass).

Clark and Evans (1954) developed the R statistic as a method to describe spatial point patterns based on nearest neighbor distances. Thompson (1956) extended Clark and Evans work to include the nearest *n* neighbors. Smith (1977) used the mean and variance of the distance to the nearest 6 neighbors to describe spatial point patterns of southeastern pine stands in more detail. Frohlich and Quednau (1994) used Clark and Evans' R statistic to describe spatial pattern for the purpose of analyzing spatial patterns formed by natural regeneration in mixed mountain forest stands.

Reed and Burkhart (1985) assessed spatial autocorrelation of tree characteristics using Moran's I statistic. The purpose of Reed and Burkhart's study was to investigate spatial autocorrelation of tree characteristics such as product, defect, species class, and basal area in forest stands. Penttinen *et al.* (1992) described forest stands as marked point processes where stem location was the point and stem attributes were the marks. Penttinen *et al.* (1992) used marked point statistics such as the mark correlation function and the pair correlation function to describe the spatial dependance of stem diameters in a spruce forest, heights in a stand of pine saplings, and heights, stem diameters, and crown lengths in a mixed birch-pine forest area. Biondi *et al.* (1994) used semi-variograms to study spatial variability of stem diameter, basal area, and 10-year periodic basal area increment in an old-growth forest stand.

Incorporating all the biotic, edaphic and climatic interactions present in a real life forest stand into a mathematical process to simulate forest stands is difficult. Average clump size, spatial point pattern of stems, and the spatial variation of stem diameter are a result of these interactions. One-acre stem maps display these interactions for the vegetation mapped, are readily available, and can be used to simulate forest stands.

2. OBJECTIVES

The objectives of this study are to (1) generate forest stands for sampling simulation using one-acre stem maps, and (2) examine and compare the spatial characteristics of the one-acre stem map with the spatial characteristics of the simulated forest stand created from the one-acre stem map. Spatial characteristics are assessed by average clump size, spatial point pattern, and spatial variability of stem diameter.

3. MATERIALS AND METHODS

3.1 One-acre stem map database

The database consisted of 11 one-acre stem maps (Appendix I). One-acre stem maps will be referred to as “stem maps”. The data were collected by the American Pulpwood Association and used for harvesting system simulations (APA, 1969). They were square and measured 208.71 feet per side. In the Cartesian coordinate system the origin of the stem map was 0,0 and the extent was 208.71,208.71 feet. Each stem map was selected to be representative of a forest stand likely to be harvested in the southeastern United States. All stem maps were from the lower coastal plain with 5 and 6 stem maps from Georgia and Florida respectively. There were two stem maps from old-field natural pine stands, five from wild pine stands, and four from pine plantations. Wild pine stands were defined as stands that developed from causes other than agricultural abandonment. The major species were *Pinus taeda* (loblolly pine), *Pinus palustris* (longleaf pine), and *Pinus elliottii* (slash pine) at densities ranging from 178 to 558 trees per acre. Table 3.1 gives a more detailed description of each stem map.

Table 3.1. Major characteristics of each stem map.

Stem map number	Origin	Age (years)	Trees per Acre	Major Species	% Dominant Species[1]	Location
1	Old Field	30	192	Longleaf, Slash	88%	GA
2	Old Field	30	200	Slash	100%	FL
3	Wild	30	251	Longleaf, Slash	64%	FL
4	Wild	22	178	Longleaf	98%	FL
5	Wild	30	285	Slash, Oak	74%	GA
6	Wild	35	259	Longleaf, Slash	88%	FL
7	Wild	35	213	Longleaf	98%	FL
8	Plantation	20	558	Loblolly	100%	GA
9	Plantation	18	180	Longleaf, Slash	90%	FL
10	Plantation	25	293	Longleaf, Slash	77%	GA
11	Plantation	12	505	Slash	100%	GA

1- Percent dominant species is the percent of total stems represented by the single most abundant species.

3.2 Introduction to the simulation procedure

One possible method to simulate forest stands using stem maps is based on the block bootstrap. Efron (1979) developed a non-parametric method to analyze data known as the bootstrap. This method involved randomly drawing samples of *n* or fewer observations with replacement from a sample of *n*. The bootstrap theory was designed to mimic the manner in which the original random data set was drawn from its population (Kotz, 1997). The original purpose of the bootstrap was to estimate the variance of a particular statistic. For example, Efron *et al*. (1986) used the bootstrap method to estimate the standard error of the Pearson correlation coefficient between students LSAT scores and their law school GPA's. Hall (1985) developed the block bootstrap to work with dependant spatial data based on an extension of Efron's (1979) work. Hall's (1985) block bootstrap resampled blocks or groups of data, from the original sequence, with replacement. The size of the blocks was based on the spatial dependance of the analysis variable.

The block bootstrap can also be used as a method to build simulated forest stands by resampling stem maps. For example, groups of trees from the stem map are sampled randomly with replacement using equal area blocks. The block samples are then placed adjacently creating a simulated forest stand. The size of the blocks would be determined by assessing the nature of spatial dependance that exists in the stem map. For example, if tree diameter is the variable of interest and trees within 30 feet of each other are autocorrelated with respect to diameter, the block size would be 30 feet by 30 feet (approximately 1/50 ac.) . These randomly drawn 1/50 acre blocks would be placed adjacently until a simulated forest stand of desired shape and size is built. The supposition is that spatial dependance of tree diameter would be preserved within the blocks but corrupted at the edges of the blocks.

In this paper, the approach taken to simulate forest stands was analogous to the block bootstrap and will be referred to as the “simulation procedure”. The simulation procedure was a two step process. The first step was to create discrete block samples of two sizes and eight different orientations from a single stem map. The second step was to randomly select samples with replacement and place them adjacently to create a simulated forest stand. With the block bootstrap randomness was in the drawing of the blocks and with the simulation procedure randomness was in the placement of the blocks. The simulation procedure used block sizes of 1-acre and 1/2-acre. The supposition was that the simulation procedure will reduce the amount of block edges, maintain not only the spatial autocorrelation of stem diameter, but also the spatial point pattern and average clump size present in the stem map.

3.3 Simulation procedure

Simulated forest stands ("simulated stands") were 49-acres and consisted of stem locations, species, stem diameter, and stem height. They were square and measured 1460.97 feet per side. In the Cartesian coordinate system the origin of the simulated stand was 0,0 and the extent was 1460.97,1460.97 feet.

The first step was to create 17 different block samples from the stem map. Sample 1 was a stem map oriented North. Samples 2, 3, and 4 were the North facing stem map rotated to the right 90, 180 and 270 degrees respectively. Sample 5 was created by taking sample 1 and flipping it upside down to create a mirror image also facing North. Rotating the mirror image (sample 5) by 90, 180 and 270 degrees to the right created samples 6, 7, and 8 respectively. Samples 9 through 16 were rectangular one-half acre blocks either 104.36 feet in the *x* direction and 208.71 feet in the *y* direction or 208.71 feet in the *x* direction and 104.36 feet in the *y* direction. Sample 9 was created using sample 1 (North facing sample) and deleting all trees which had an *x* coordinate of greater than 104.36 feet leaving a rectangular one-half acre block. Rotating sample 9 by 90, 180, and 270 degrees to the right created samples 10, 11, and 12 respectively. Sample 13 was created by taking sample 5 (North Facing mirror image) and deleting all trees with an *x* coordinate greater that 104.36 feet. Samples 14, 15, and 16 were created by rotating sample 13 by 90, 180, and 270 degrees to the right. Sample 17 was created by taking sample 1(North facing sample) and deleting all trees with *x* and *y* coordinates greater than 52.18 feet, leaving a one-quarter acre block.

The procedure to create discrete block samples was slightly modified to work with plantations. Stem maps from plantations had 9 samples created because rows of trees were forced to run the same direction. The 9 samples corresponded to samples 1, 3, 5, 7, 9, 11, 13, 15, and17 from above.

The second step was to randomly select samples with replacement and build each simulated stand row by row. A row was considered 1460.97 in the *x* direction and 104.36 feet in the *y* direction. One sample was randomly selected and placed at coordinate position 0, 0. Next, another sample was randomly selected from the full set of samples and the appropriate value was added to the *x* coordinate so to place the current selection adjacent to the previous selection. This was done until the East edge of the last sample on the row equaled 1460.97 feet. The last sample for a row was randomly selected from the from the full set of samples until it fit. For example, if a row needed a one-half-acre block to be completed, the random selection procedure continued until a one-half-acre sample that fit was selected. This procedure filled all of the first row and some of the second row because one-acre samples and rectangular samples with the long side vertical are 208.71 feet in the *y* direction. For this reason, after the first row was completed the procedure went to the empty positions in the second row and randomly selected from the samples and placed an appropriate sample in the empty position. This procedure continued until samples were needed for the top row (*y* coordinate 1356.61 feet). At this point the one-quarter-acre sample was added as a possible selection if the other samples would overstep the boundary of the simulated stand.

3.4 Spatial characteristics

3.4.1 Average clump size

Ecologist began using both random and exhaustive quadrats counts to determine point patterns of plant communities in the mid 1930's (Greig-Smith, 1952). A Poisson series was used to estimate the proportion of quadrats containing 0,1,...,*n* individuals for a random point pattern. Random point patterns followed a Poisson distribution where the variance/mean ratio of quadrat counts equaled one. It followed that if the variance/mean ratio of quadrat counts was greater than 1 the point pattern was overdispersed and underdispersed if the variance/mean ratio was less than 1 (Clapham, 1936). Cressie (1993) described complete spatial randomness as the absence of any structure and noted that all stochastic processes have components of randomness. Overdispersed point patterns tended to be aggregated or clumpy and underdispersed point pattern tended toward uniformity.

Greig-Smith (1952) used contiguous quadrats to classify point patterns and describe the scale of pattern intensity or average clump size. This method required counts of stems from blocks of grid units. In this paper the grid unit was 1/256 acres. The analysis was done with blocks of 1, 2, 4, 8, 16, 32, 64, 128, and 256 grid units and were 1/256, 1/128, 1/64, 1/32, 1/16, 1/8, 1/4, 1/2, and 1 acre respectively. A nested analysis of variance was performed on the count of stems that fell in blocks of grid units (Equation 3.1). Greig-Smith's (1952) method was only used to estimate the average clump size.

This was identified as the block size with the greatest mean square value that exceeded the acceptance region developed by Cressie (1993) (Equation 3.2). Cressie's (1993) acceptance region was based on a normal approximation under the hypothesis that the expected mean square is the same for blocks of *r* and *r*/2 grid units. Average clump size was compared between each simulated stand and the stem map from which it was created to determine if the simulation procedure reproduced the average clump size.

$$SS_r = \frac{1}{2r}\sum_{i=1}^{m}\left(A_i - B_i\right)^2$$

$$MS_r = {}^{SS_r}\!/_{m} \qquad \textbf{Equation 3.1}$$

$$A_r = m^{-1} MS_{r/2}\,\chi^2_m \qquad \textbf{Equation 3.2}$$

SS_r = The between-block sum of squares from blocks of r grid units.

MS_r = The between-block mean square from blocks of r grid units.

A_r = The 95% acceptance region for MS_r.

r = The number of grid units per block.

A_i and B_i = The number of stems in the i^{th} pair of blocks.

m = The number of pairs of blocks.

3.4.2 Spatial point pattern

The development of distance methods to determine spatial point patterns followed quadrat methods. Clark and Evans (1954) developed the R statistic to describe spatial point patterns as random, clumpy, or uniform based on the ratio of mean and expected mean nearest neighbor distance. The expected mean nearest neighbor distance for a random point pattern was density specific (number of points per unit area) and based on a Poisson function where any sector of a circle with *r* radius contains exactly *y* individuals. It followed that if the circle was about a randomly selected point, the proportion of nearest neighbors less than *r* units away was also related to the Poisson function and the expected nearest neighbor distance (*r*) of an individual was inversely proportional to the square root of the density of the point pattern. Naturally occurring point patterns are usually isotropic and therefore one sector of a circle is generally used to calculate the expected mean nearest neighbor distance for a random point pattern of a specified density (Clark *et al.*, 1954).

Clark and Evans' (1954) method was extended to the nearest six neighbors by Thompson (1956). Thompson (1956) found that n^{th} nearest neighbor distances were related to the Chi-square distribution and the expected mean distance to the n^{th} nearest neighbor in a random point pattern was

$$E(r_n) = \frac{1}{\sqrt{m}} \frac{(2n)!n}{(2^n \cdot n!)^2} \qquad \textbf{Equation 3.3}$$

The second moment of the distribution was

$$E(r_n^2) = \frac{n}{\pi \cdot m} \qquad \textbf{Equation 3.4}$$

where

n = The rank of the neighbor of interest (1, 2, 3, or 4th closest neighbor)

m = The density of points in the area measured in the same units as the distance.

Smith (1977) further classified point patterns into four categories based on deviations from expected mean n^{th} nearest neighbor distance (under a random distribution) and their respective variance using a graphical analysis. The point patterns were:

1. Random (Figure 3.1): "In a random distribution of a set of points on a given area, it is assumed that any given point has the same chance of occurring in an sub-area as any other point, that any sub-area of specified size has the same chance of receiving a point as any other sub-area of that size, and that the placement of each point has not been influenced by that of any other point" (Clark and Evans, 1954).
2. Overdispersion Type I (Figure 3.2): A clumpy stand with variance of the distance to the nearest four neighbors greater than expected for a random distribution and stems randomly distributed within clumps (Smith, 1977)
3. Overdispersion Type II (Figure 3.3): A clumpy stand with variance of the distance to the nearest four neighbors less than expected for a random distribution and stems uniformly distributed within clumps (Smith, 1977)
4. Underdispersion (Figure 3.4): Uniform distribution of stems (non-clumpiness) with variance of the distance to the nearest four neighbors less than expected for a random distribution and with homogeneity of density of stems throughout the stand (Smith, 1977).

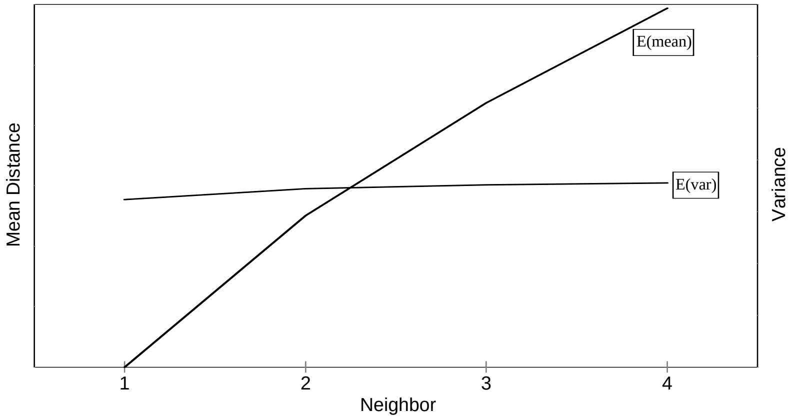

Figure 3.1. Expected mean and variance of the distance to the first through fourth nearest neighbors for a randomly distributed population.

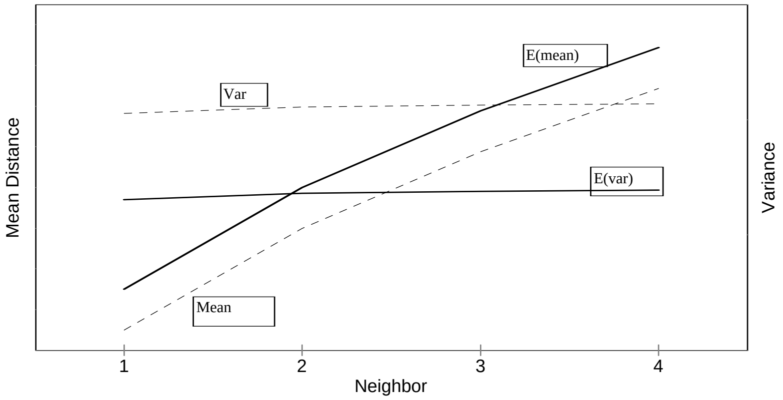

Figure 3.2. Trend in the mean and variance of the distance to the first through fourth nearest neighbors from an overdispersed type I point pattern. The solid line and broken line represent a random point pattern and overdispersed type I point pattern respectively.

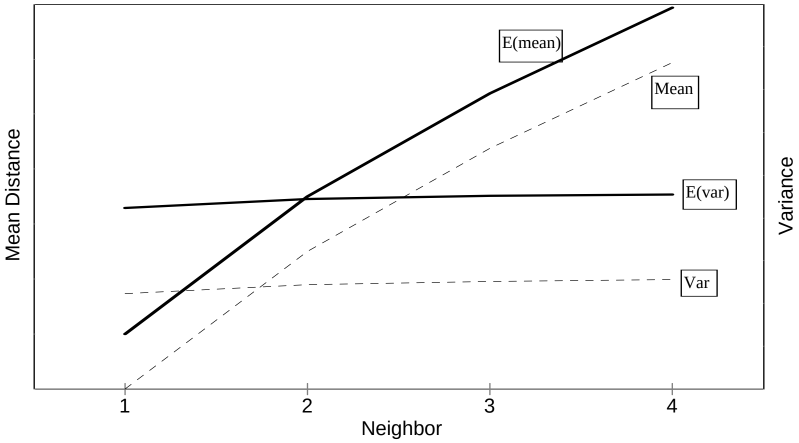

Figure 3.3. Trend in the mean and variance of the distance to the first through fourth nearest neighbors from an overdispersed type II point pattern. The solid line and broken line represent a random point pattern and overdispersed type II point pattern respectively.

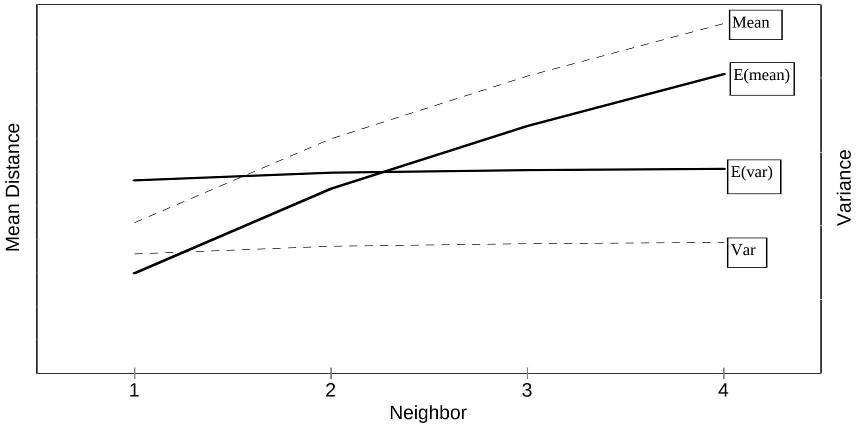

Figure 3.4. Trend in the mean and variance of the distance to the first through fourth nearest neighbors from an underdispersed point pattern. The solid line and broken line represent a random point pattern and underdispersed point pattern respectively.

The spatial point pattern of each stem map and simulated stand was classified using Smith's (1977) method. Only trees whose distance to the n^{th} nearest neighbor was less than the distance to the nearest boundary line were used when identifying point patterns (Frohlich *et al.*, 1995). Expectations were calculated using all stems.

The Kolomogrov-Smirnov two sample test was used to further identify the influence of the simulation procedure on neighbor distances in simulated stands. A distribution of the first, second, third, and fourth mean neighbor distances was created for each stem map and simulated stand using the bootstrap method. For example, 20 first nearest neighbor distances, from a stem map, were randomly selected with replacement and averaged. This was done 100 times on the stem map and the result was a distribution of 100 mean first nearest neighbor distances. The same procedure was used for a simulated stand created with the stem map. Stem map and simulated stand first nearest neighbor distributions were then compared with the Kolomogrov-Smirnov two sample test. This comparison was done for each of the one through four nearest neighbors for each simulated stand.

3.4.3 Spatial variability of stem diameter

Semi-variograms display the structure of spatial variability a point attribute has in a given area (Deutsch and Journel, 1992). The semi-variance is calculated by determining the distance from each point in an area to every other point in that area and calculating one-half of the average squared difference (semi-variance) of the point attribute by separation distance groups (lag distance). Semi-variogram analysis assumes intrinsic stationarity. Intrinsic stationarity is the premise that the mean of the variable of interest is constant but unspecified and the semi-variance is only dependant on separation distance (Kitanidis, 1997).

Semi-variograms are plots of semi-variance by lag distance. In semi-variogram terminology, the nugget refers to a discontinuity at lag distance 0 (Figure 3.5). The sill refers to the maximum value of semi-variance and the range refers to the lag distance value where the semi-variance reaches 95 percent of its maximum (Figure 3.5). When semi-variance increases as separation distance increases spatial autocorrelation is present because objects close together are more alike than object far apart (Figure 3.5). There is no spatial autocorrelation when the semi-variance does not change as distance increase (Figure 3.5). When semi-variance shows a sinusoidal pattern as distance increase the population has periodicity (Figure 3.5).

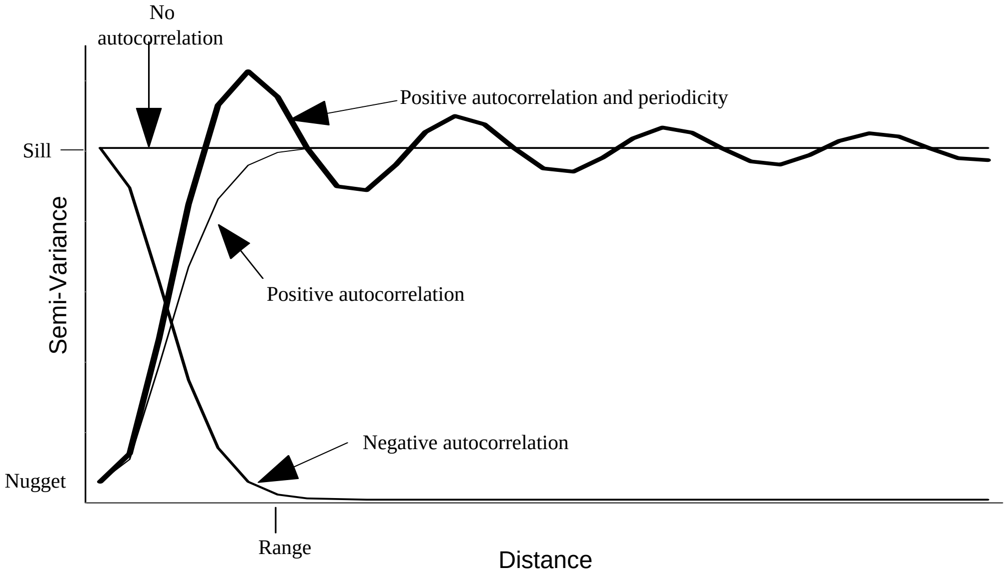

Figure 3.5. Structures of spatial variation using semi-variogram analysis. Sill, nugget, and range values are valid for the line displaying positive autocorrelation.

Cressie and Hawkins (1980) developed a robust semi-variogram estimator for data that deviate from a normal distribution or have outliers. The final form of the Cressie and Hawkins robust semi-variogram estimator is

$$\overline{\gamma}(h) = \frac{1}{2\left(0.457 + \frac{0.494}{N(h)}\right)} \left\{\frac{1}{N(h)}\right\} \sum_{1}^{N(h)} \sqrt{\left|V_i - V_j\right|} \qquad \textbf{Equation 3.5}$$

where

h = lag distance

N(h) = number of pairs of at lag distance *h*

V = value of the variable at locations *i* and *j*.

Semi-variograms are modeled to explain spatial variation as a continuous function. Some commonly used variogram models are the linear (Equation 3.6), Gaussian (Equation 3.7), and wave (Equation 3.8) models. Linear models are used to model linear trends in spatial variation. Gaussian models are sigmoidal and account for strong relationships at short distances. Wave models account for both positive and negative autocorrelation and are used to model spatial relationships with periodicity. Cressie (1985) suggests weighted least squares regression to determine the coefficients for variogram models. The weights are based on the number of pairs at each lag distance and put the most emphasis on semi-variogram values near lag distance 0 (Equation 3.9).

$$\gamma(h) = \begin{cases} 0 & h = 0 \\ c_0 + c_1\|h\| & h \neq 0 \end{cases}$$ **Equation 3.6**

$$\gamma(h) = \begin{cases} 0 & h = 0 \\ c_0 + c_1\left(1 - e^{-3\left(\frac{\|h\|}{a}\right)^2}\right) & h \neq 0 \end{cases}$$ **Equation 3.7**

$$\gamma(h) = \begin{cases} 0 & h = 0 \\ c_0 + c_1\left(1 - \frac{\sin(\pi\|h\|/a)}{\pi\|h\|/a}\right) & h \neq 0 \end{cases}$$ **Equation 3.8**

$$W_h = \frac{N(h)}{2[\gamma(h)]^2}$$ **Equation 3.9**

$\gamma(h) =$ Variogram model value at lag distance h.

C_0 = Nugget effect

C_0+C_1 = Sill value for models other than linear

a = Range

W_h = Weight for weighted least square regression.

$N(h)$ = The number of pairs at lag distance h.

Robust semi-variograms of stem diameter were created for each stem map and simulated stand. Stem diameter was used because it is more dependant on growing space than on site quality. Stem diameter of each stem map was examined for log normality and square-root normality using the Shapiro-Wilk test. The W statistic approaches 1 as the data approach normality in the Shapiro-Wilk test. W-values of stem diameter, log stem diameter, and square-root stem diameter were compared for each stem map. No transformation was used because neither transformation out-performed the un-transformed data with respect to the W-value. Semi-variogram models of stem diameter were fitted by weighted least squares for each stem map. Semi-variograms were visually inspected to determine changes in the spatial variability of stem diameter as a result of the simulation procedure. The semi-variograms were also used to identify presence of periodicity induced by the simulation procedure, in the simulated stands, past the maximum stem separation distance of the Stem map. The maximum separation distance for a square one-acre stem map was 295.2 feet.

4. RESULTS

4.1 Simulated forest stands

Ten simulated stands were created for each stem map resulting in 110 simulated stands. The same one-acre and half-acre block samples were used and their placement was randomized for each of the ten simulated stands created from a single stem map. For example, the seventeen block samples for stem map 1 were the same for all simulated stands but the placement of the samples changed for each simulated stand created with stem map 1.

Simulated stands ranged in density from 8,430 (172 trees per acre) to 27,368 (558 trees per acre) stems. For each simulated stand, density (trees per acre) and major species percentage remained consistent with the stem map from which it was created. Simulated stands represented old field stands (Figure 4.1), wild stands (Figure 4.2), and plantations (Figure 4.3).

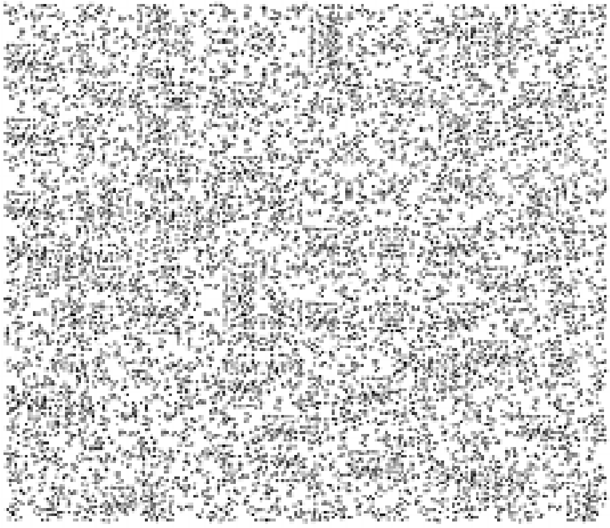

Figure 4.1. Scatter plot of a simulated old field stand (192 trees per acre) with a random spatial point pattern created with stem map 1.

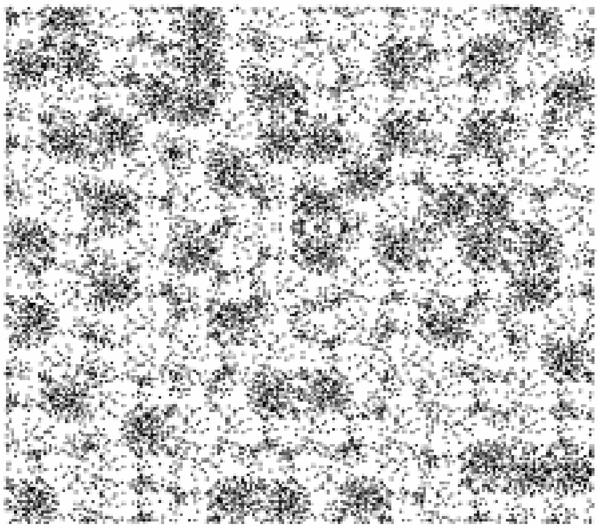

Figure 4.2. Scatter plot of a simulated wild stand (259 trees per acre) with a overdispersed type I spatial point pattern created with stem map 6

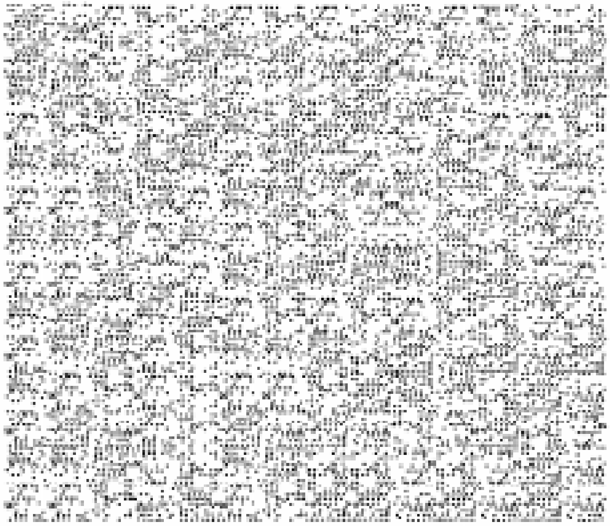

Figure 4.3. Scatter plot of a simulated plantation (180 trees per acre) with a underdispersed spatial point pattern created with stem map 9.

4.2 Spatial characteristics

4.2.1 Average clump size

The average clump size was estimated as the block size with the greatest mean square value (Greig-Smith, 1952) outside the 95% acceptance region developed by Cressie (1993). The average clump size from each simulated stand was estimated and compared with the average clump size of the stem map from which it was created. For example, the average clump size for stem map 7 and a simulated stand created with stem map 7 was 1/4-acre (Figure 4.4). The simulation procedure maintained the average clump size on 25%, 92%, and 100% of simulated stands created with stem maps from old field stands, wild stands, and plantations respectively (Table 4.1). Across stand origins, the simulation procedure maintained the average clump size on 83% of the simulated stands (Table 4.1).

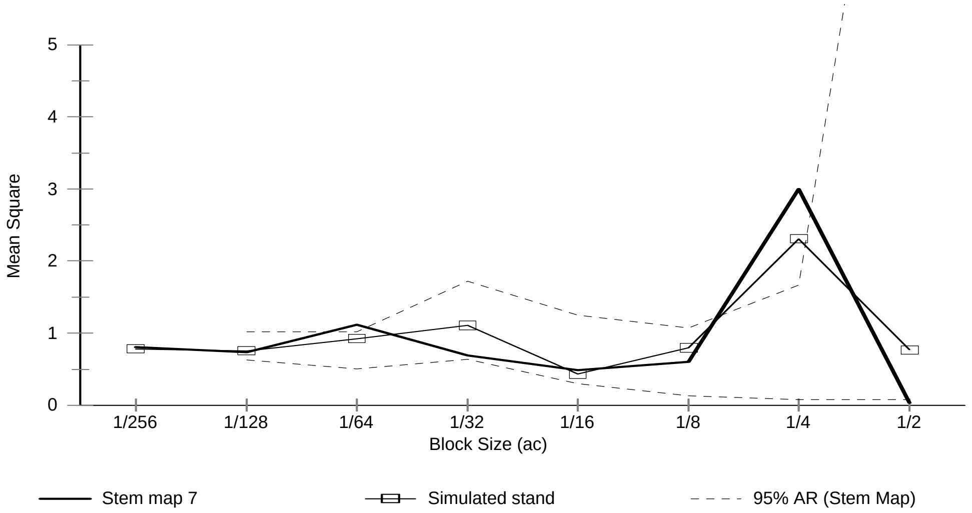

Figure 4.4. Plot of mean square versus block size, together with the 95 % acceptance region (AR). The average clump size was 1/4-acre for both stem map 7 and the simulated stand created with stem map 7.

Table 4.1. Effects of the simulation procedure on average clump size based on a comparison between stem maps and simulated stands.

Stem map number	Origin	Average clump size of stem map (acres) [1]	Simulated Stands [2] 1/8(acre)	1/4(acre)	1/2(acre)	Total
1	Old Field	1/4	0	4	6	
2	Old Field	1/4	0	1	9	5/20=25%
3	Wild	1/8	8	2	0	
4	Wild	1/2	0	0	10	
5	Wild	1/8	8	2	0	
6	Wild	1/4	0	10	0	
7	Wild	1/4	0	10	0	46/50=92%
8	Plantation	*	*	*	*	
9	Plantation	*	*	*	*	
10	Plantation	*	*	*	*	
11	Plantation	1/8	10	0	0	40/40=100%
Total						91/110=83%

1- * Denotes no statistically detectable average clump size as defined by Cressie (1993).

2- The number of simulated stands out of 10 with average clumps sizes of 1/8, 1/4, or 1/2 acres.

4.2.2 Spatial point pattern

Spatial point pattern, based on the four nearest neighbor distances, was classified for each stem map and simulated stand using Smith's (1977) method (Figures 4.5 and 4.6). Two stem maps were classified as random, one was overdispersed type II, four were overdispersed type I, and four were classified as undispersed (Table 4.2). All simulated stands had the same spatial point pattern as the stem map from which they were created (Table 4.2). Although the point pattern classification was not changed as a result of the simulation procedure, the mean and variance of the n^{th} nearest neighbor distance generally increased (Figure 4.6). This was particularly evident at the third and fourth nearest neighbor level for some simulated stands (Figure 4.6).

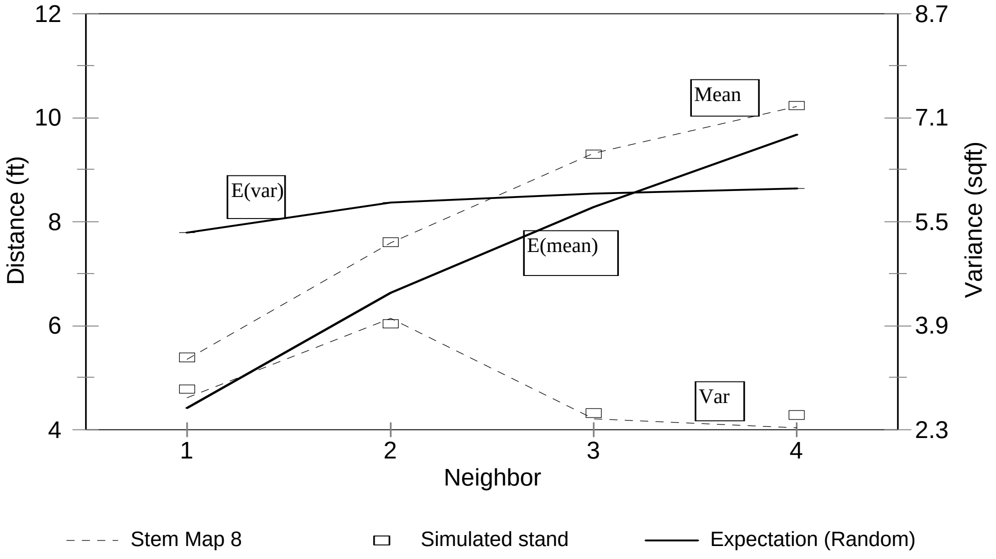

Figure 4.5. Trend in the mean and variance of the first through fourth nearest neighbor distances from stem map 8, a simulated stand created with stem map 8, and the expectation for a random point pattern. Both the stem map and simulated stand are classified as an underdispersed spatial point pattern (Smith, 1977).

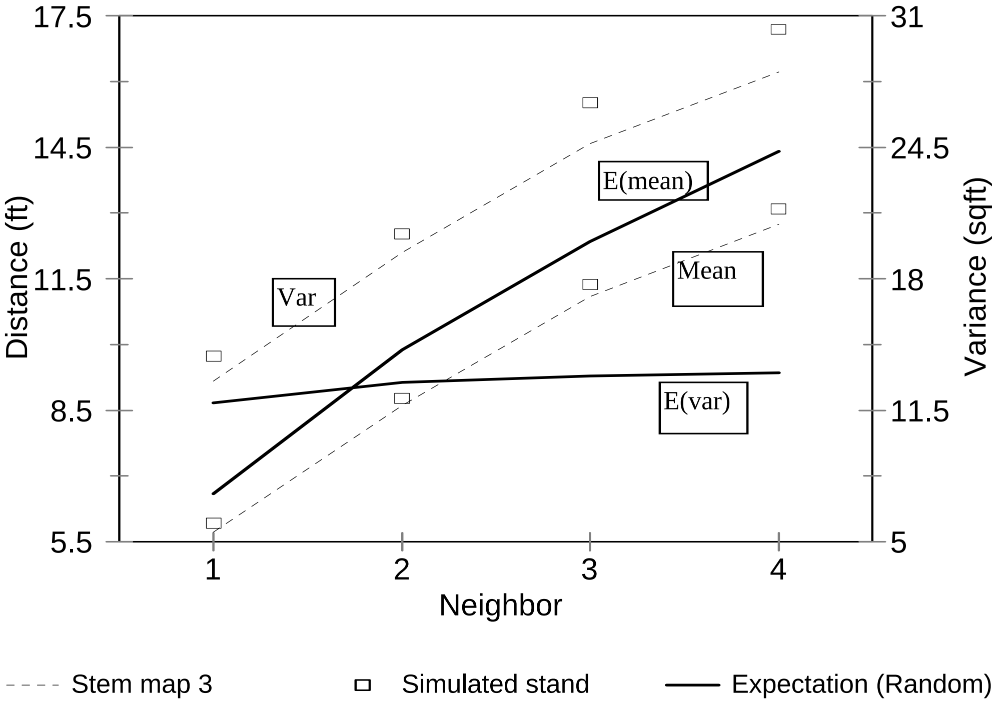

Figure 4.6. Trend in the mean and variance of the first through fourth nearest neighbor distances from stem map 3, a simulated stand created with stem map 3, and the expectation of a random point pattern. Both the stem map and simulated stand were classified as an overdispersed type I spatial point pattern (Smith, 1977).

Table 4.2. Effects of the simulation procedure on spatial point patterns and the distribution of mean one through four nearest neighbor distances based on a comparison between stem maps and simulated stands.

Stem map number	Origin	Spatial point pattern[1]	Mean distance to first neighbor in feet[2]	Mean distance to second neighbor in feet[2]	Mean distance to third neighbor in feet[2]	Mean distance to fourth neighbor in feet[2]	Total
1	Old Field	R (10)	7.73(3)	11.61(3)	14.83(2)	17.16(10)	1/20=5%
2	Old Field	U (10)	8.45(8)	11.75(8)	14.00(0)	15.92(0)	
3	Wild	O I. (10)	5.71(7)	8.61(7)	11.10(8)	12.74(3)	16/50=32%
4	Wild	O I. (10)	6.27(3)	10.23(3)	12.62(0)	14.99(0)	
5	Wild	O I. (10)	6.00(10)	8.77(10)	11.29(2)	13.35(10)	
6	Wild	O I. (10)	6.65(9)	9.35(9)	11.32(4)	13.18(3)	
7	Wild	R (10)	7.95(8)	11.34(8)	13.91(10)	16.11(10)	
8	Plantation	U (10)	5.36(10)	7.59(10)	9.31(8)	10.22(8)	28/40=70%
9	Plantation	U (10)	10.23(10)	12.71(10)	14.64(10)	16.58(6)	
10	Plantation	O II. (10)	5.73(10)	8.98(10)	11.26(6)	12.94(9)	
11	Plantation	U (10)	6.48(10)	8.16(10)	9.54(10)	10.67(9)	
Total		110/110=100%	88/110=80%	88/110=80%	60/110=55%	68/110=60%	

1- O I: Overdispersion Type I
O II: Overdispersion Type II
U: Underdispersion
R: Random
Bracketed number represent the number of simulated stands maintaining the stem maps spatial point pattern.

2- Bracketed number represents the number of simulated stands maintaining the stem maps distribution of mean nth nearest neighbor distances.

Distributions of mean first, second, third, and fourth nearest neighbor distances were created using Efron’s (1979) bootstrap method. These distributions were then compared between stem maps and simulated stands using the Kolomogrov-Smirnov two sample test at the 5% level. For example, the distribution of mean first nearest neighbor distances was compared between stem map 3 and each of the 10 simulated stands created with stem map 3. Seven out of the 10 simulated stands created with stem map 3 maintained the distribution of mean first nearest neighbor distances (Table 4.2).

The simulation procedure maintained the distribution of mean distances to the first, second, third, and fourth nearest neighbors 88, 88, 60, and 68 times respectively (Table 4.2). The distributions of all four nearest neighbor distances was maintained by the simulation procedure on 5%, 32%, and 70% of the simulated stands from old field, wild, and plantation stem maps respectively (Table 4.2). Across stand origins, the simulation procedure maintained the distributions of mean distances to the four nearest neighbors on 41% of the simulated stands.

4.2.3 Spatial variability of stem diameter

Robust semi-variograms of stem diameter were created for each stem map and simulated stand. Stem map semi-variogram models were used to report the various structures of stem diameter spatial variation (Table 4.3). The model used for each stem map was chosen from the linear, Gaussian, or wave model based on the shape of the robust semi-variogram. For example, the robust semi-variogram of stem map 8 showed evidence of positive autocorrelation (Figure 4.7) so it was modeled with the Gaussian model type (Table 4.3). Semi-variograms of simulated stands were visually compared to the stem maps from which they were created (Figures 4.7, 4.8 and 4.9). This comparison included visually assessing the nugget, sill, range and overall structure of the robust semi-variograms from each stem map and simulated stand. The simulation procedure did not appear to reproduce the spatial variation of stem diameter when stem maps with a coefficient of variation of stem diameter above 40% and percent dominant species below 75% were used (Table 4.3 and Figure 4.8). The parameters changed by the simulation procedure were the sill and shape of the semi-variogram. For example, the semi-variogram for stem map 3 had a sill of 8 and periodicity while a semi-variogram of a simulated stand created with stem map 3 had a sill of roughly 7 and showed little evidence of periodicity (Figure 4.8). The range did not appear to be changed by the simulation procedure. There was no evidence of periodicity in simulated stands at distances greater than the maximum stem separation distance (295.2 feet) for a square one-acre stem map (Figure 4.7). The simulation procedure maintained the spatial variation of stem diameter present in the original data 100%, 60%, and 100% for simulated stands created from stem maps from old field stands, wild stands, and plantations respectively (Table 4.3). Across stand origins, the simulation procedure maintained the structure of spatial variation of stem diameter on 82% of the simulated stands (Table 4.3).

Table 4.3. Effects of the simulation procedure on the spatial variation of stem diameter based on a comparison between stem maps and simulated stands.

Stem map number	Origin	Major species	Percent domminant species	CV (diameter)	Co[1]	C1[1]	a[1]	Model type[2]	Total
1	Old Field	Longleaf, Slash	88%	28.9	6.50	0.001	*	Linear (10)	20/20=100%
2	Old Field	Slash	100%	32.7	12.46	-10.319	37.81	Gaussian (10)	
3	Wild	Longleaf, Slash	64%	45.5	3.05	5.171	85.97	Wave (0)	30/50=60%
4	Wild	Longleaf	98%	36.6	5.60	1.795	111.79	Wave (10)	
5	Wild	Slash, Oak	74%	47.5	6.66	0.012	*	Linear (0)	
6	Wild	Longleaf, Slash	88%	35.3	4.16	1.940	76.55	Wave (10)	
7	Wild	Longleaf	98%	27.1	2.67	2.280	55.72	Gaussian (10)	
8	Plantation	Loblolly	100%	23.5	0.72	1.503	8.83	Gaussian (10)	40/40=100%
9	Plantation	Longleaf, Slash	90%	26.6	4.89	-1.566	20.64	Gaussian (10)	
10	Plantation	Longleaf, Slash	77%	36.4	3.32	2.362	19.37	Gaussian (10)	
11	Plantation	Slash	100%	25.2	2.95	0.000	*	Linear (10)	
Total								90/110=82%	

1- *Co* = Nugget effect
Co+C1 = Sill value for wave and Gaussian models
a = range

2- Linear model (Equation 3.6)
Gaussian model (Equation 3.7)
Wave model (Equation 3.8)
Bracketed number is the number of simulated stands maintaining the stem maps nugget, sill, range, and structure of spatial autocorrelation.

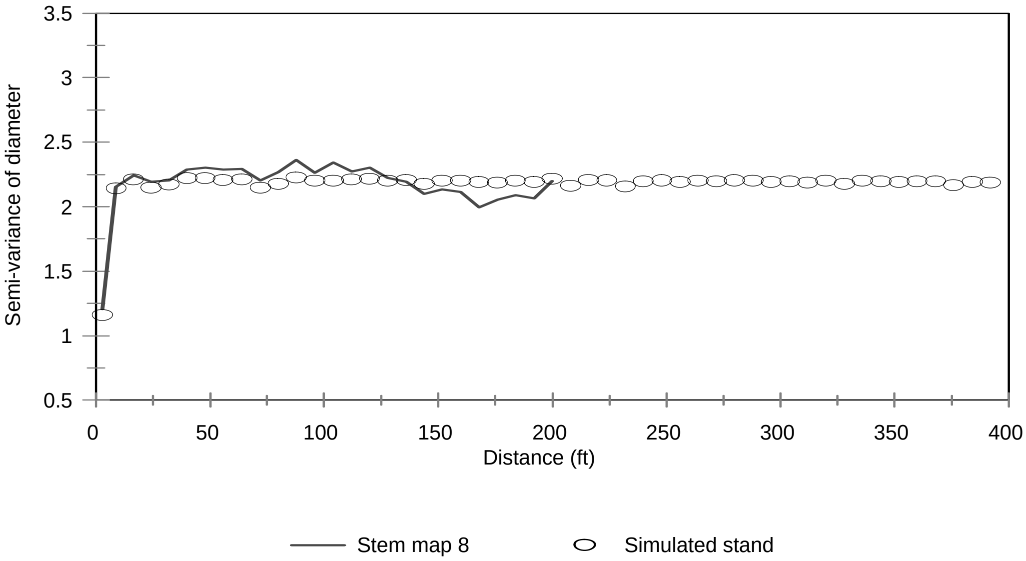

Figure 4.7. Robust semi-variogram of stem map 8 and a simulated stand created with stem map 8. Stem map 8 was from a plantation.

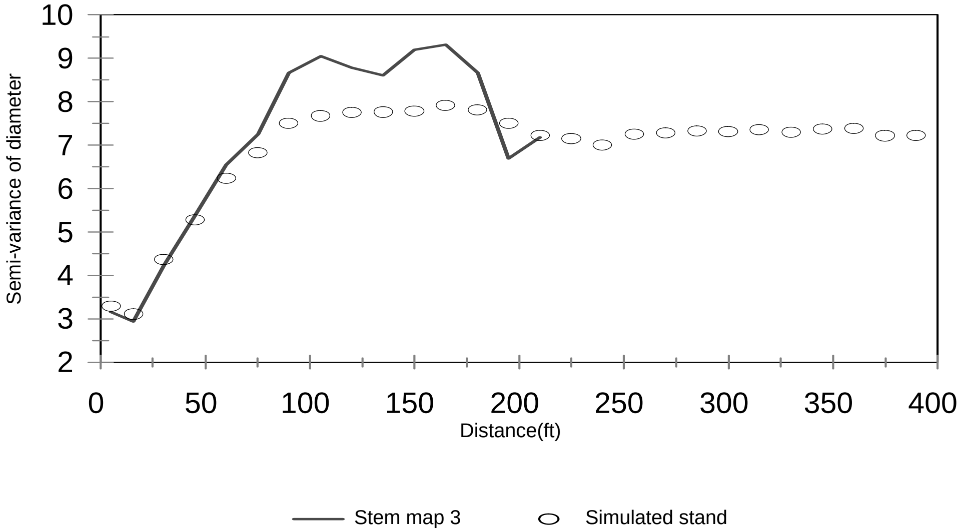

Figure 4.8. Robust semi-variogram of stem map 3 and a simulated stand created with stem map 3. Stem map 3 was from a wild stand.

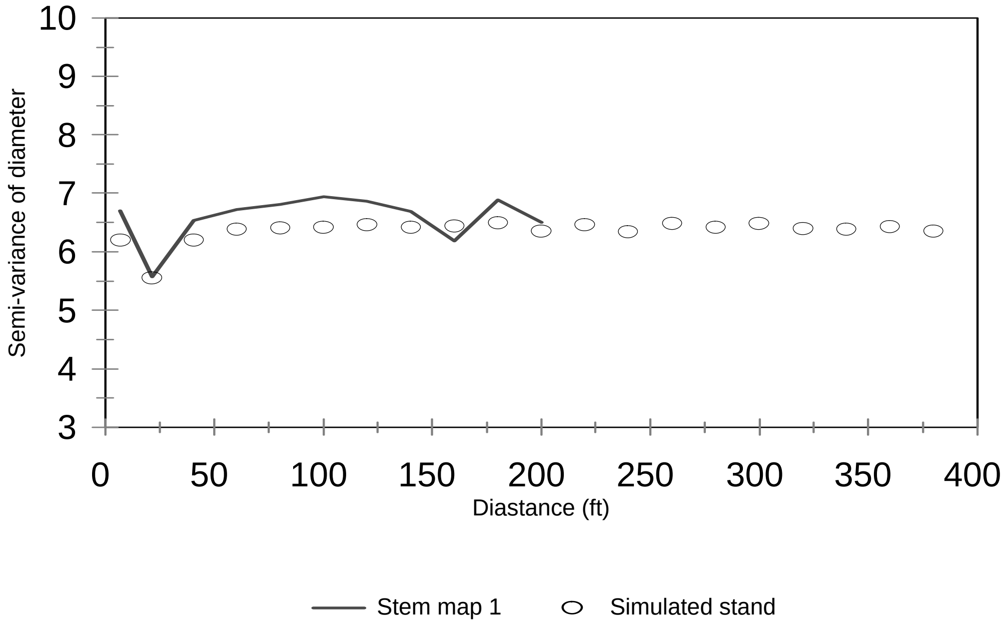

Figure 4.9. Robust semi-variogram of stem map 1 and a simulated stand created with stem map 1. Stem map 1 was an old field stand.

4.2.4 Combined spatial characteristics

The simulation procedure maintained the average clump size, spatial point pattern, and spatial variability of stem diameter on 25%, 60%, and 100% of the simulated stands generated from stem maps representing old field natural pine stands, wild pine stands, and pine plantations respectively (Table 4.4). Across origins, the simulation procedure maintained the average clump size, spatial point pattern, and spatial variation of stem diameter on 68% the simulated stands (Table 4.4).

Table 4.4. The ratio of simulated stands maintaining their respective stem maps average clump size, spatial point pattern, and spatial variation of stem diameter.

Stem map number	Origin	Ratio of simulated stands maintaining the stem maps spatial characteristics	Total
1	Old Field	4/10	
2	Old Field	1/10	5/20=25%
3	Wild	0/10	
4	Wild	10/10	
5	Wild	0/10	
6	Wild	10/10	
7	Wild	10/10	30/50=60%
8	Plantation	10/10	
9	Plantation	10/10	
10	Plantation	10/10	
11	Plantation	10/10	40/40=100%
Total		75/110=68%	

5. DISCUSSION

The simulation procedure destroyed the structure of data at the boundaries of the blocks because that is where new information was created. In this research, the influence of the new information on the spatial characteristics was the chief concern. The simulation procedure used one-acre and half-acre blocks to reduce the amount of boundary and maintain the spatial point pattern, average clump size, and spatial variability of stem diameter contained in the original data. This was not achieved in all simulated stands. The influence of block boundaries using the simulation procedure predominantly occurred at the third and fourth nearest neighbor distance levels (Table 4.2). Boundaries created by the simulation procedure likely influenced the distance to the fifth through n^{th} nearest neighbors more than the distance to the first through fourth nearest neighbors because as n increased the probability of crossing a boundary also increased. When average clump size changed as a result of the simulation procedure it was because the distance to neighbors making up clumps crossed block boundaries and changed. When average clump size changed as a result of the simulation procedure, it only changed by one block size (Table 4.1 and Figure 5.1).

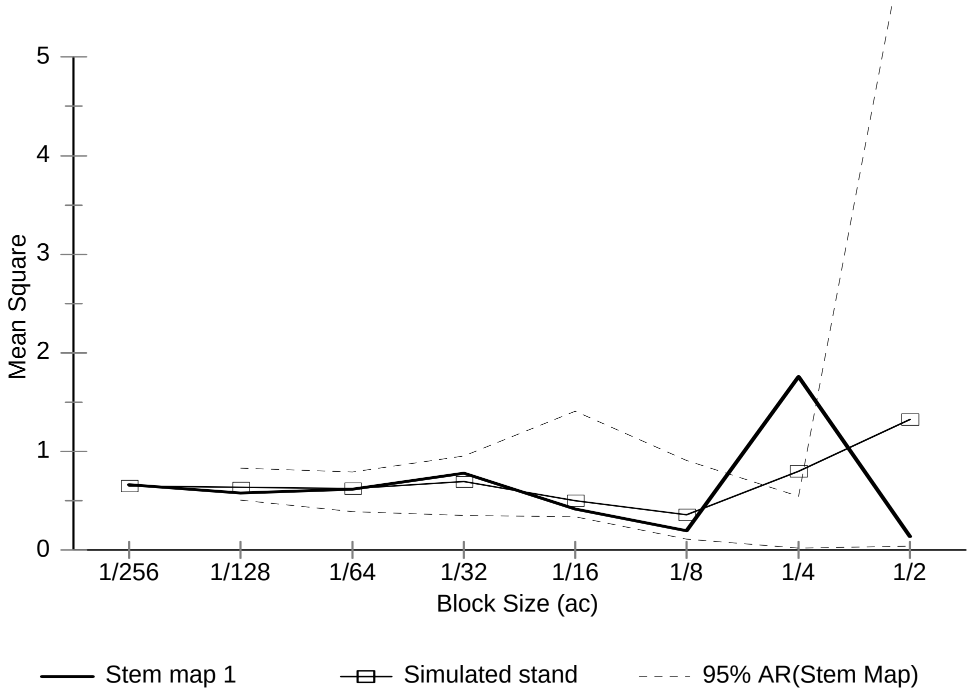

Figure 5.1. Plot of mean square versus block size, together with the 95% acceptance region (AR). The average clump size was 1/4-acre for stem map 1 and 1/2-acre for a simulated stand created with stem map 1.

The simulation procedure also had a small dampening effect on spatial variability of stem diameter in some simulated stands (Figures 4.8 and 4.9). In most simulated stands the dampening effect did not change the structure of spatial variability (Figure 4.9). A drastic reduction and a change in structure of spatial variability of stem diameter occurred when using stem maps 3 and 5 to create simulated stands and is illustrated in Figure 4.8. The dampening effect did not influence the overall structure in most cases (Table 4.3).

The applicability of the simulation procedure relates to the second order stationarity of the one-acre stem map used. Stem maps with second order stationarity have equal mean stem diameter across the region and the variance of stem diameter is only dependant on stem separation distance. Second order stationarity can be assessed using moving window statistics however, the size of the window has an influence on the assessment of stationarity. For example, a one-acre stem map may be appear stationary if the size of the moving window is 1/16-acres but non-stationary if the moving window is 1/25-acres. Because second order stationarity is difficult to identify, a graph of stem locations (*x*, *y* positions), the dominant species percentage, and the coefficient of variation for stem diameter should be used to determine the applicability of the simulation procedure with respect to a particular one-acre stem map. Stem location graphs should be void of large clumps of stems in any 1/4-acre area one-acre stem map. On a percentage basis, 1/4-acre area should not have more than 40% of the total number of stems. The dominant species percentage should be above 75% and the coefficient of variation of stem diameter should be below 40%. For example, if these guidelines were followed, the simulation procedure would have maintained the average clump size, spatial point pattern, and spatial variation of stem diameter on 65/80 (81%) of the simulated stands. Using the simulation procedure on stem maps without the above mentioned characteristics has the potential to simulate stands with enough new information at block boundaries that the overall spatial characteristics from the stem maps may be altered.

Describing the spatial characteristics of the stem maps was a combined function of the spatial point pattern and spatial attributes of the points. This function was not fully described by any one metric (spatial point pattern, average clump size, robust semi-variogram of stem diameter).

One area for further research is developing a metric to assess spatial point pattern and the spatial relationship between point attributes simultaneously. This is important because a metric capable of this may more completely describe the spatial characteristics of a marked point process. One possible method would be to combine Moran's I statistic with nearest neighbor point pattern descriptors. For example, point patterns can be classified based on the mean distance to the first nearest neighbor and autocorrelation can be assessed using the first nearest neighbor as the neighborhood. There are expectations (for random processes) for both the mean nearest neighbor distance (Clark *et al.*, 1954) and the Moran's I spatial autocorrelation statistic (Moran, 1950) using the first nearest neighbor as the neighborhood definition. It should follow that there is an expectation for a random point pattern with no autocorrelation between points. If this expectation exists then the deviated from it would describe marked point processes.

Reed and Burkhart (1985) documented positive and negative spatial autocorrelation of basal area in several southeastern forest stands. They explained both types of spatial autocorrelation as a result of competition. Negative autocorrelation was an artifact of substantial establishment of an understory (Reed *et al.*, 1985). In simple terms, negative autocorrelation of stem basal area was due to a large number of small trees growing next to big trees. Positive autocorrelation was evident where stands were fairly uniform and not yet at carrying capacity and where the difference between tree basal area was mainly from microsite variability (Reed *et al.*, 1985). Results from the stem diameter semi-variogram analysis of this project in conjunction with the examination of 3D scatter plots of x-position, y-position, and stem diameter of stem maps supported Reed and Burkhart's (1985) hypothesis.

Stem map semi-variograms of stem diameter showed evidence of negative and positive autocorrelation, periodicity, and no autocorrelation (Table 4.3). This evidence supported Biondi's (1994) findings. Biondi (1994) found positive autocorrelation of stem diameter and basal area at separation distances up to 25 meters. Positive autocorrelation of stem diameter was present in stem map 4 (wild stand, predominantly longleaf pine) at separation distances up to 112 feet (Table 4.3- range). A wave model was used to describe the spatial variability of stem diameter in stem map 4 because there was evidence of periodicity (Table 4.3). In total, 8 stem maps showed evidence of positive autocorrelation, 4 stem maps showed evidence of periodicity, 2 stem maps showed evidence of negative autocorrelation, and 2 stem maps showed no evidence of spatial autocorrelation of stem diameter (Table 4.3).

Assessing spatial autocorrelation of the mean or total of stem attributes between forest inventory plots rather than individual stems is an area for further research. Between plot autocorrelation of mean or total diameter or volume has a much larger impact on conventional (single systematic sample) timber cruising than single stem autocorrelation. For example, when plots show positive autocorrelation the distance between sample plots should be larger than the range of autocorrelation. If sample plots are within the range of positive autocorrelation there is redundant information being gathered. Also, confidence interval width may be overestimated when using the standard variance formula with samples from autocorrelated populations. For this reason, sample size estimations based on pre-sampling may also be overestimated resulting in over cruising.

6. CONCLUSION

The simulation procedure maintained the spatial point pattern of the original data however, the mean and variance of nearest neighbor distance significantly altered particularly at the third and fourth nearest neighbor level. Average clump size and spatial variation of stem diameter were maintained by the simulation procedure on 83% and 82% of the simulated stands respectively. A plot of stem locations (*x*, *y* positions), species percentages, and the coefficient of variation of stem diameter can be used to determine the applicability of the stand simulation procedure. Stem location graphs should have less than 40% of the stems in any 1/4-acre area, dominant species percentage should be above 75%, and the coefficient of variation of stem diameter should be below 40%. Stem maps with the above mentioned characteristics can readily be used to create simulated forest stands using this simulation procedure.

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8. APPENDIX I: One-acre stem map database

Stem map number	1		Percent Longleaf pine	88%
Location	GA		Mean dbh (in.)	9.1
Origin	Old Field		Standard deviation (dbh)	2.6
Average age (years)	30		Range (dbh)	3.0--15.8
Trees per acre	192		Mean height (ft.)	68.9
Basal area per acre (sqft.)	94.4		Standard deviation (height)	13
Major species	Longleaf, Slash		Range (height)	17--87

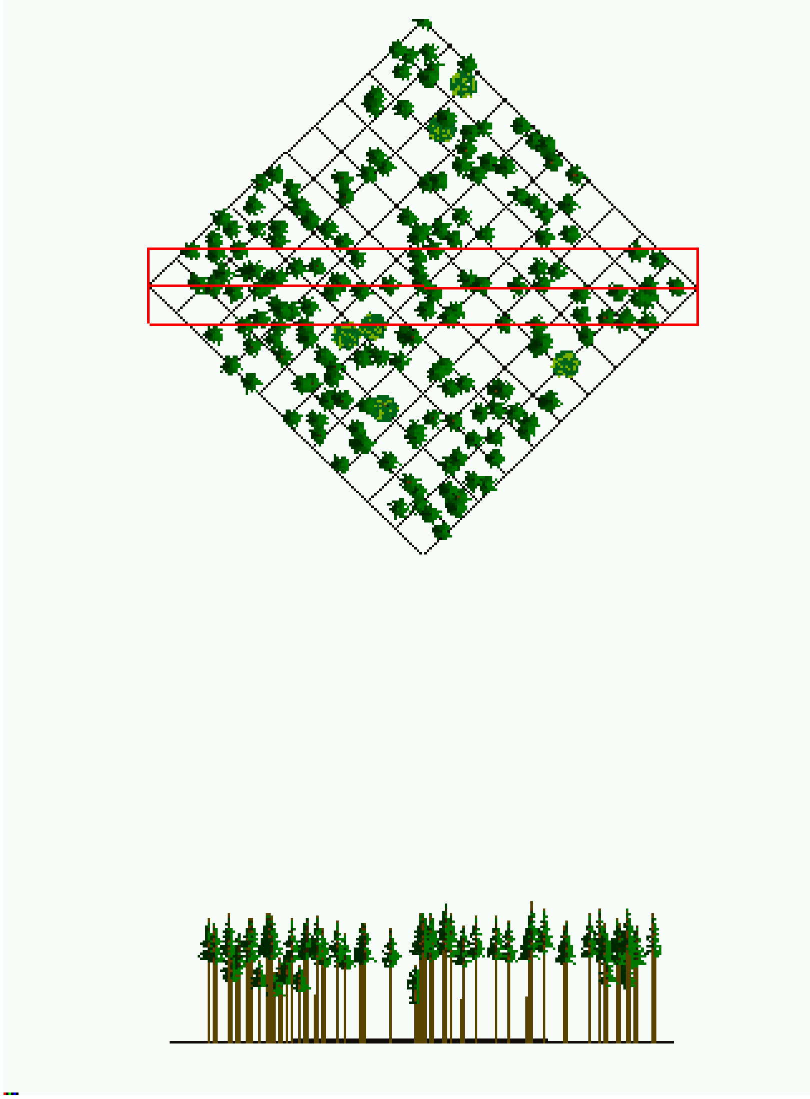

Figure 8.1. Characteristics, overhead view, and a 40 ft. profile strip of stem map 1.

Stem map number	2		Percent Slash pine	100%
Location	FL		Mean dbh (in.)	8.2
Origin	Old Field		Standard deviation (dbh)	2.7
Average age (years)	30		Range (dbh)	3.0--13.2
Trees per acre	200		Mean height (ft.)	64.1
Basal area per acre (sqft.)	81.6		Standard deviation (height)	14.4
Major species	Slash		Range (height)	28--81

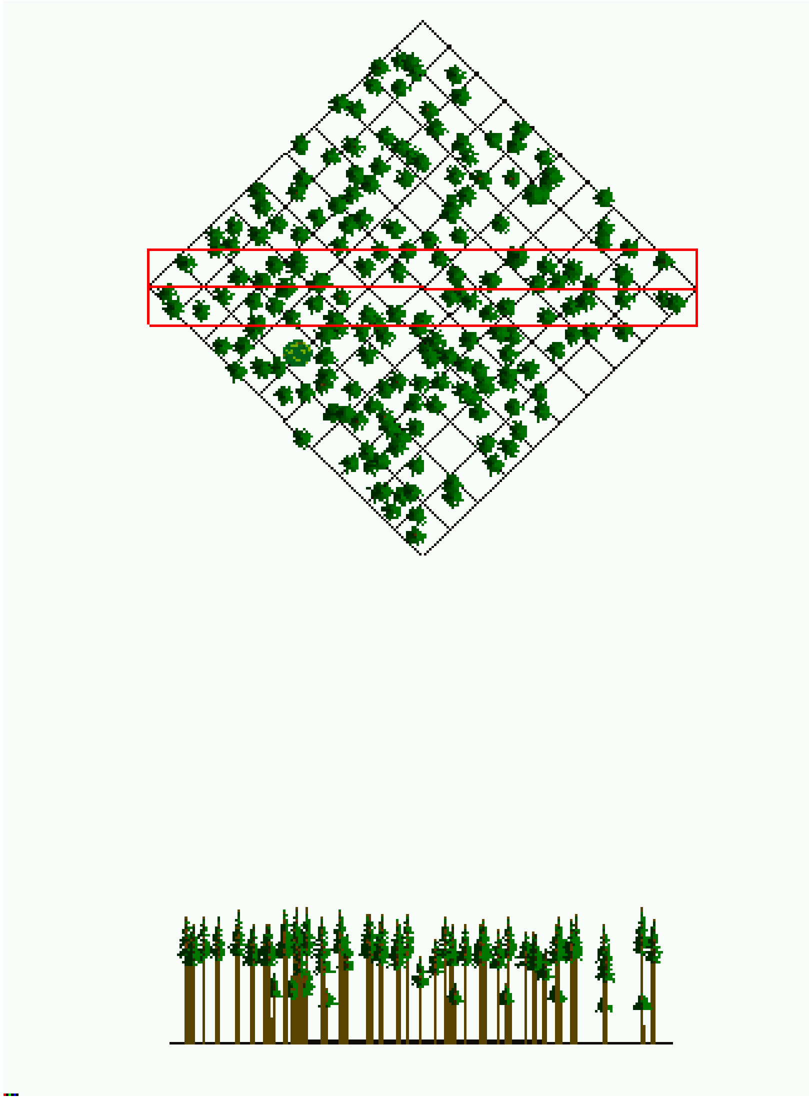

Figure 8.2. Characteristics, overhead view, and a 40 ft. profile strip of stem map 2.

Stem map number	3		Percent Longleaf pine	64%
Location	FL		Mean dbh (in.)	6.2
Origin	Wild		Standard deviation (dbh)	2.8
Average age (years)	30		Range (dbh)	2.6--1.3
Trees per acre	251		Mean height (ft.)	52.2
Basal area per acre (sqft.)	62.9		Standard deviation (height)	14.8
Major species	Longleaf, Slash		Range (height)	20--82

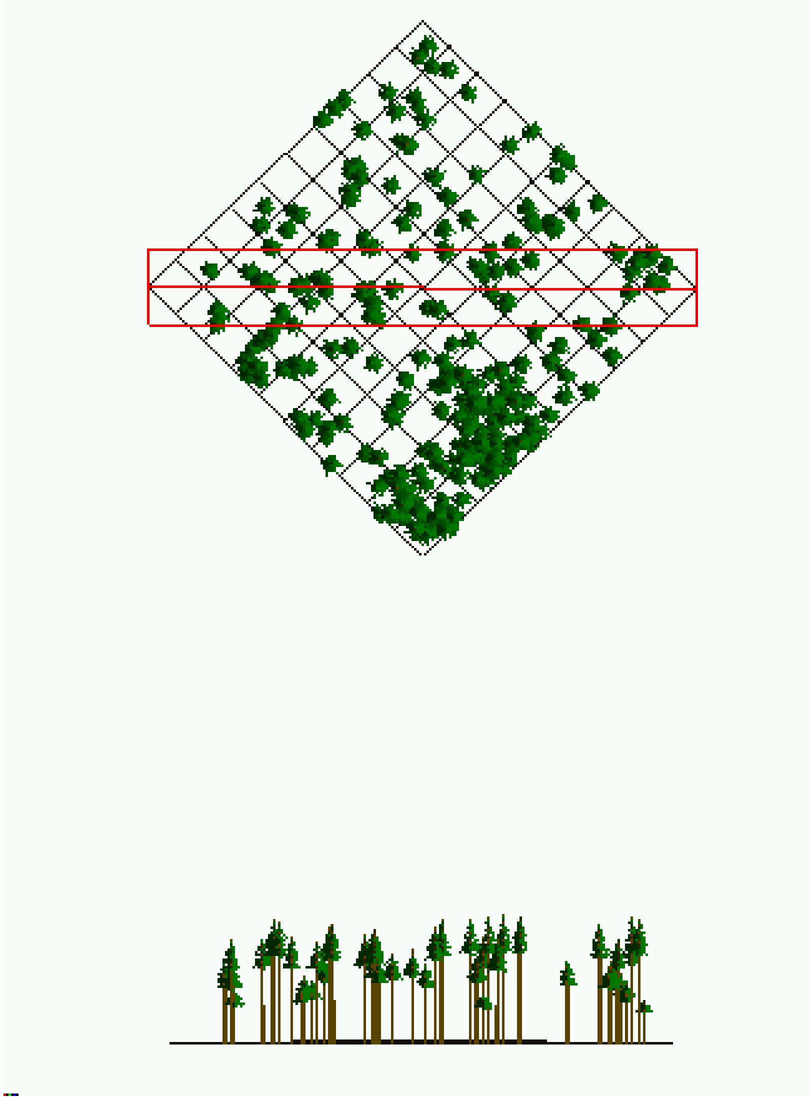

Figure 8.3. Characteristics, overhead view, and a 40 ft. profile strip of stem map 3.

Stem map number	4		Percent Longleaf pine	98%
Location	FL		Mean dbh (in.)	7
Origin	Wild		Standard deviation (dbh)	2.6
Average age (years)	22		Range (dbh)	3.0--11.9
Trees per acre	178		Mean height (ft.)	49.2
Basal area per acre (sqft.)	54.6		Standard deviation (height)	12.1
Major species	Longleaf		Range (height)	17--69

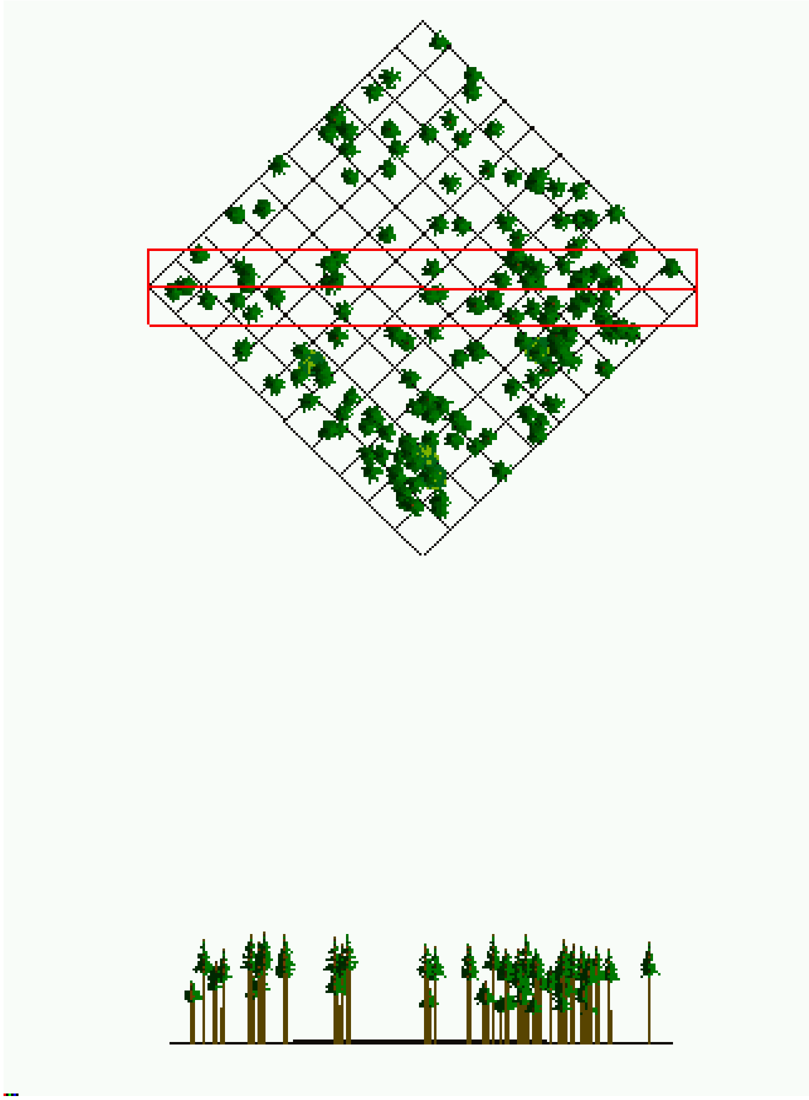

Figure 8.4. Characteristics, overhead view, and a 40 ft. profile strip of stem map 4.

Stem map number	5		Percent Slash pine	74%
Location	GA		Mean dbh (in.)	6.4
Origin	Wild		Standard deviation (dbh)	3
Average age (years)	30		Range (dbh)	2.9--16.8
Trees per acre	285		Mean height (ft.)	44.2
Basal area per acre (sqft.)	77.6		Standard deviation (height)	13.7
Major species	Slash, Oak		Range (height)	18--71

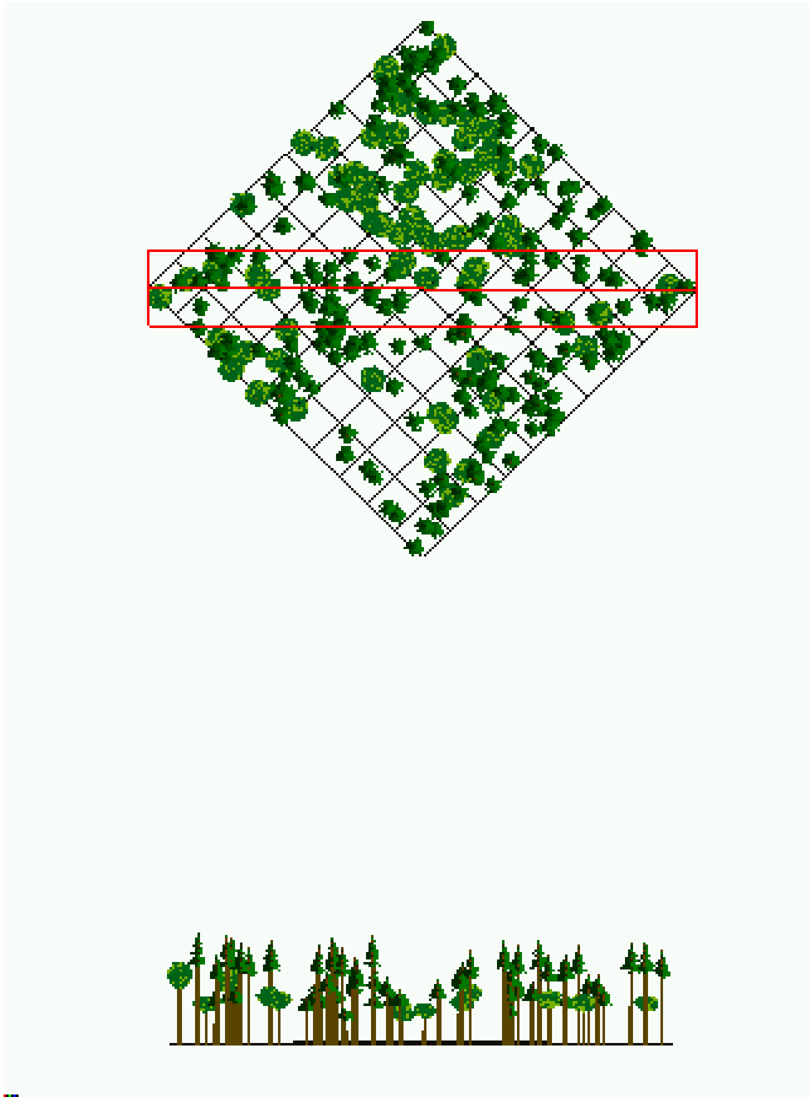

Figure 8.5. Characteristics, overhead view, and a 40 ft. profile strip of stem map 5.

Stem map number	6		Percent Longleaf pine	88%
Location	FL		Mean dbh (in.)	6.8
Origin	Wild		Standard deviation (dbh)	2.4
Average age (years)	35		Range (dbh)	2.9--14.1
Trees per acre	259		Mean height (ft.)	54.8
Basal area per acre (sqft.)	72.8		Standard deviation (height)	12.2
Major species	Longleaf, Slash		Range (height)	17--79

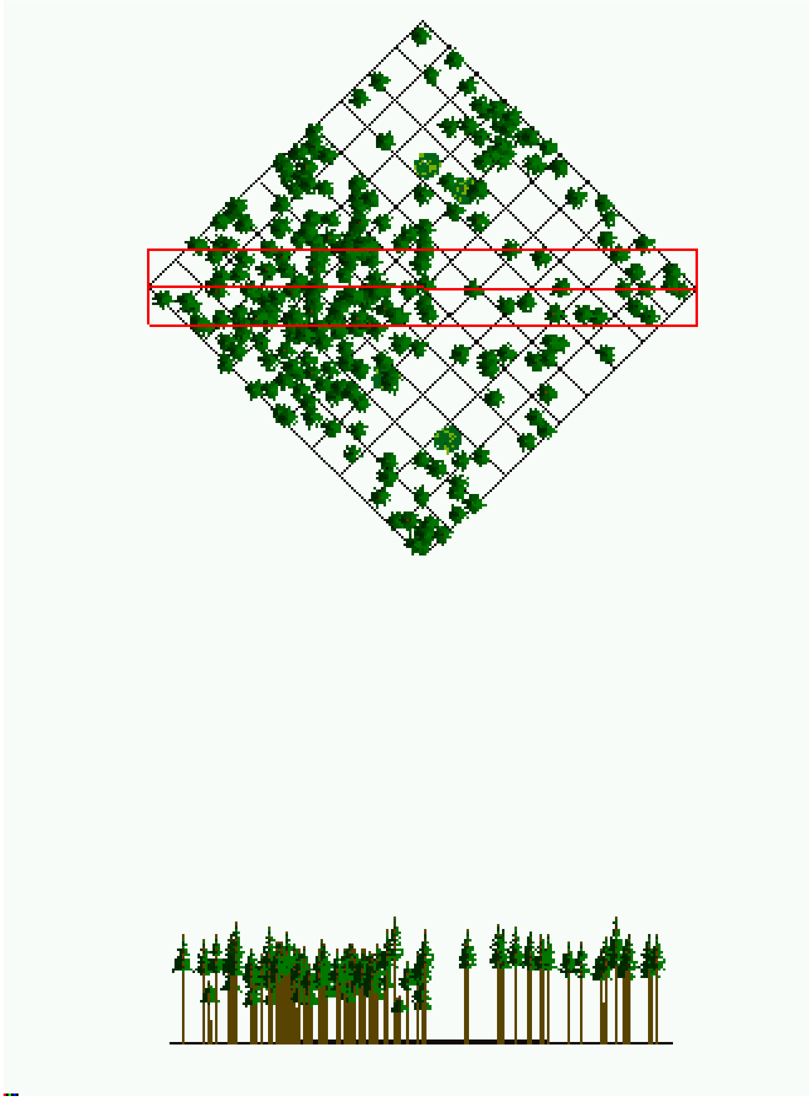

Figure 8.6. Characteristics, overhead view, and a 40 ft. profile strip of stem map 6.

Stem map number	7		Percent Longleaf pine	98%
Location	FL		Mean dbh (in.)	8
Origin	Wild		Standard deviation (dbh)	2.2
Average age (years)	35		Range (dbh)	3.0--12.9
Trees per acre	213		Mean height (ft.)	59.6
Basal area per acre (sqft.)	79.8		Standard deviation (height)	10.2
Major species	Longleaf		Range (height)	26--75

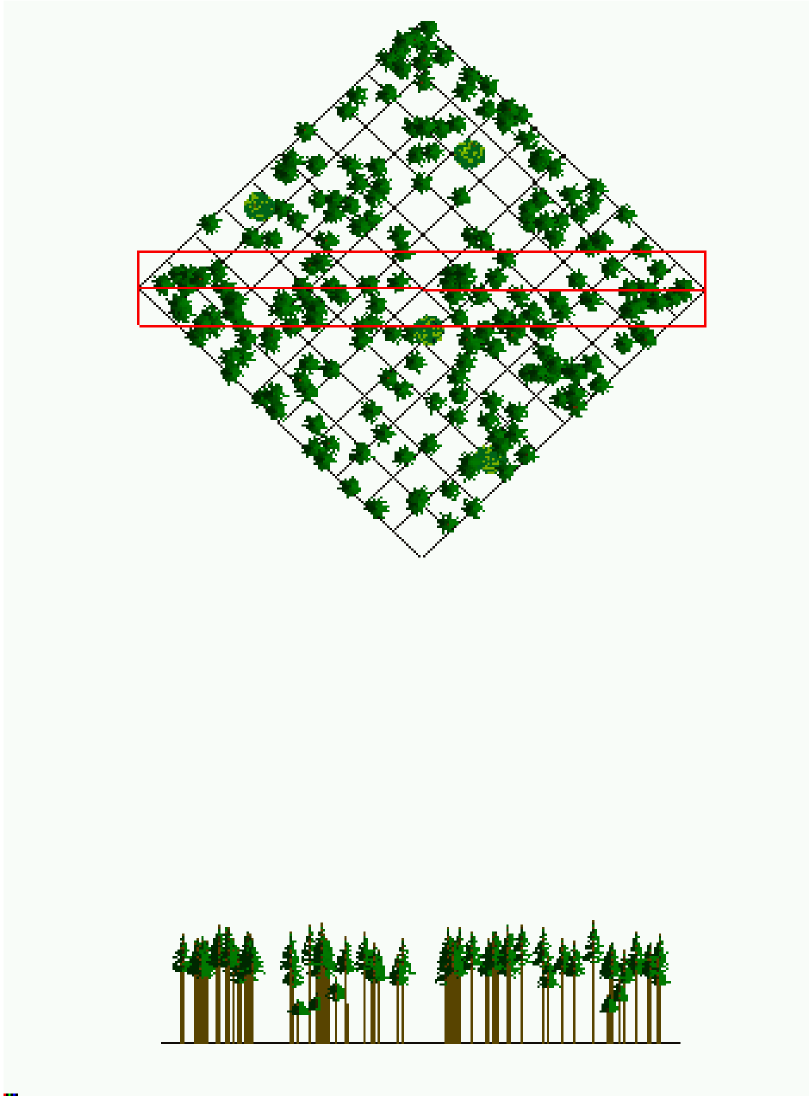

Figure 8.7. Characteristics, overhead view, and a 40 ft. profile strip of stem map 7.

Stem map number	8		Percent Loblolly pine	100%
Location	GA		Mean dbh (in.)	6.4
Origin	Plantation		Standard deviation (dbh)	1.5
Average age (years)	20		Range (dbh)	2.4--13.0
Trees per acre	558		Mean height (ft.)	46.7
Basal area per acre (sqft.)	132.2		Standard deviation (height)	6.3
Major species	Loblolly		Range (height)	18--61

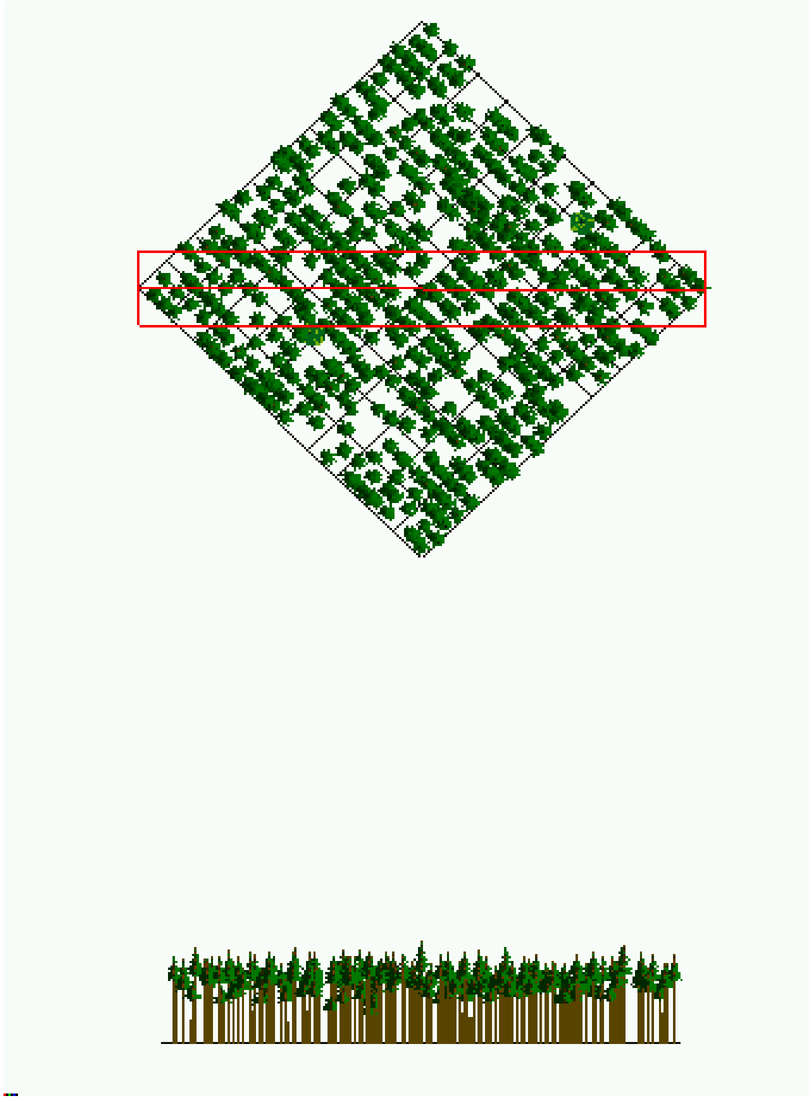

Figure 8.8. Characteristics, overhead view, and a 40 ft. profile strip of stem map 8.

Stem map number	9		Percent Longleaf pine	90%
Location	FL		Mean dbh (in.)	7.1
Origin	Plantation		Standard deviation (dbh)	1.9
Average age (years)	18		Range (dbh)	1.5--10.8
Trees per acre	180		Mean height (ft.)	46.1
Basal area per acre (sqft.)	52.9		Standard deviation (height)	9.8
Major species	Longleaf, Slash		Range (height)	9--59

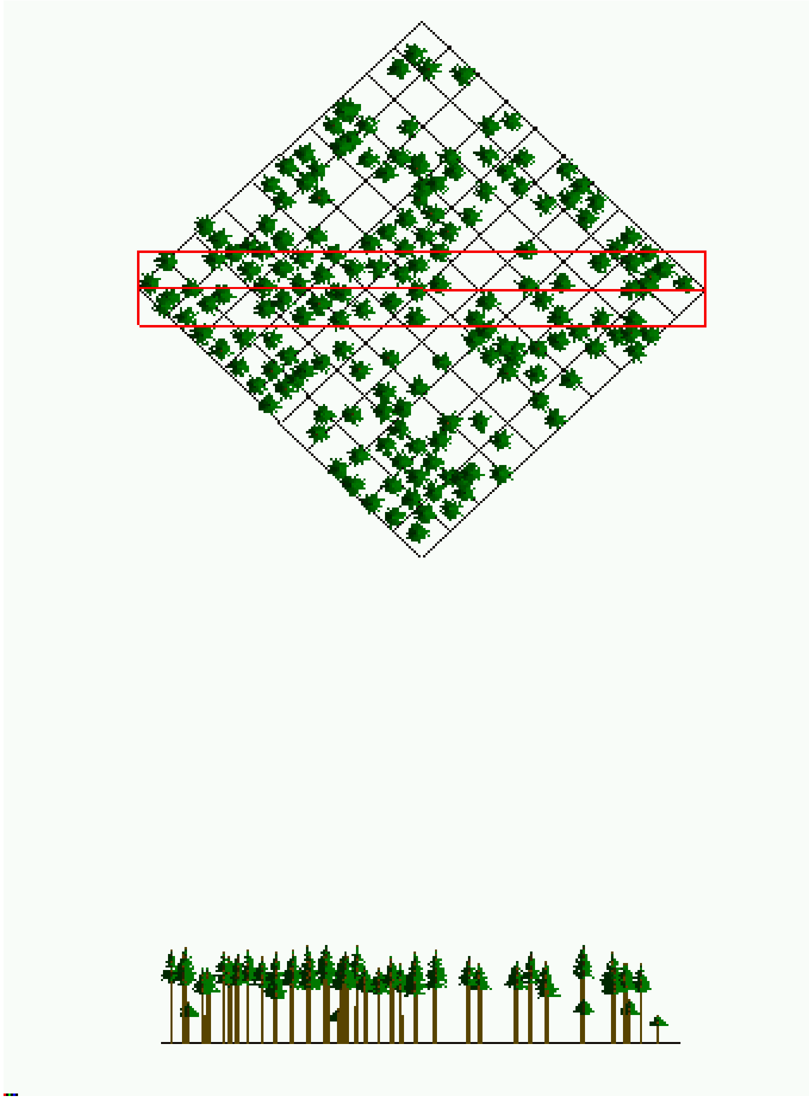

Figure 8.9. Characteristics, overhead view, and a 40 ft. profile strip of stem map 9.

Stem map number	10		Percent Longleaf pine	77%
Location	GA		Mean dbh (in.)	6.9
Origin	Plantation		Standard deviation (dbh)	2.5
Average age (years)	25		Range (dbh)	3.0-14.1
Trees per acre	293		Mean height (ft.)	41.3
Basal area per acre (sqft.)	85.6		Standard deviation (height)	6.8
Major species	Longleaf, Slash		Range (height)	20--54

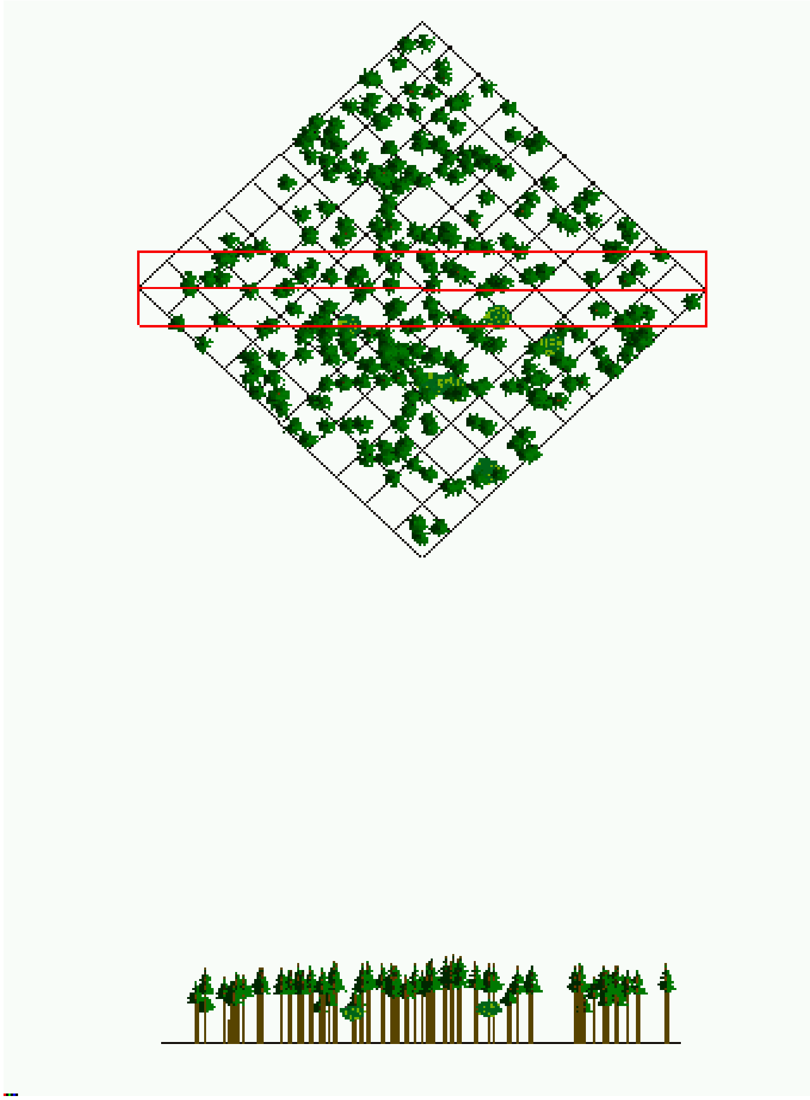

Figure 8.10. Characteristics, overhead view, and a 40 ft. profile strip of stem map 10.

Stem map number	11		Percent Slash pine	100%
Location	GA		Mean dbh (in.)	6.7
Origin	Plantation		Standard deviation (dbh)	1.7
Average age (years)	12		Range (dbh)	3.0--13.2
Trees per acre	505		Mean height (ft.)	33.3
Basal area per acre (sqft.)	131.8		Standard deviation (height)	6
Major species	Slash		Range (height)	15--53

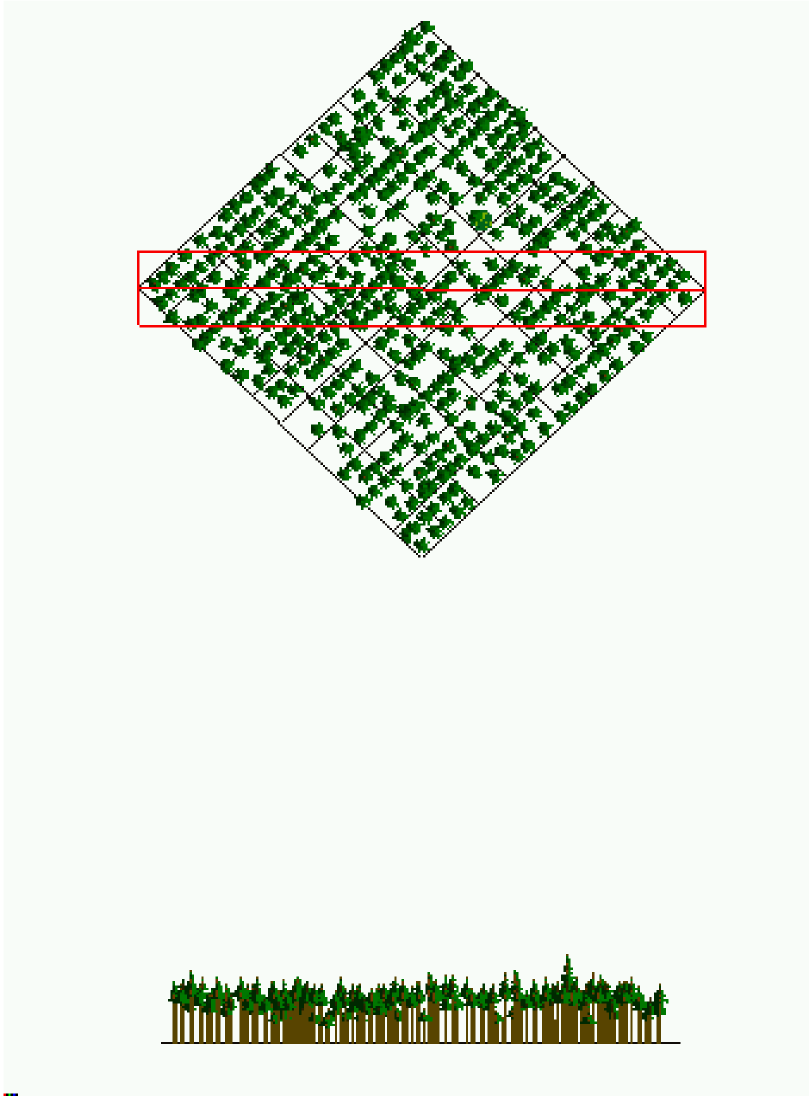

Figure 8.11. Characteristics, overhead view, and a 40 ft. profile strip of stem map 11.