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A simulation study of hardwood rootstock populations in young loblolly pine plantations

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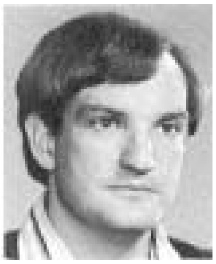

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ABSTRACT

A computer program to simulate spatial distribution *of* hardwood rootstock populations is presented. Nineteen 3 to 6 yearold loblolly pine (Pinus taeda L.) plantations in Alabama and Georgia were measured to provide information for the simulator. Spatial pattern, expressed as Pielou's nonrandomness index (PNI), ranged from 0.47 to 2.45. Scatterplots illustrated no relationship between pattern, species relative density, site preparation, or stand age.

Newnham's point pattern generator was modified to reduce execution time. Equations to predict program inputs as a function *of* PNI and desired number *of* points were developed for uniform, random, and randomly clumped populations. Total rootstock height distribution was fitted using a two-parameter, left- and right-truncated Weibull function. Crown area was determined conditionally by total rootstock height. The simulator may be used to generate populations for evaluating different sampling methods for hardwood rootstock attributes or in individual tree growth and yield models.

INTRODUCTION

An estimated 25.3 million acres of commercial timberland in the southern United States is occupied by southern pine plantations and the acreage is expected to increase. Although pines are the species of interest in these machine and hand-planted plantations, hardwood and herbaceous vegetation are also present. Control of this competing vegetation has been shown to have a positive effect on pine growth and yield (Knowe et al. 1985). Forest managers need accurate information regarding the level of competing vegetation in order to evaluate the need for or type of vegetation control. Operational sampling methods need to be evaluated regarding their effectiveness in obtaining this information.

One factor which has been shown to affect the accuracy of some sampling methods is the spatial distribution of the units being sampled. Spatial pattern of plants within a plant community has been correlated with inter- and intraspecific competition, soil type, soil moisture and aeration, animals, fire and other disturbances, and seed dispersal mechanisms (Greig-Smith 1979 and Kershaw 1963). Three types of spatial distribution in plants are generally recognized - uniform, random, and clumped distributions (Hutchinson 1953).

The performance of many density sampling techniques as a function of spatial distribution has been studied (Byth 1982, Skellam 1952, Payandeh and Ek 1971, Warren and Batcheler 1979). Ideally the reliability of a sampling method should not be affected by the spatial distribution of the sample population. Additionally a sampling method used to estimate the level of competing hardwood vegetation in southern pine plantations should be simple to implement so as to reduce cost and facilitate training.

Examination of potential sampling methods can be made in a field situation. The advantage of this approach is that conditions are realistic. However, replication of field sampling studies is often costly and comparison of sample estimates with population parameters is often not possible. An approach that overcomes the disadvantages of field trials and permits comparison of several sampling methods on the same population as well as allowing examination of the same method on several populations is simulation. This method has been widely used in sampling studies.

This paper describes the development of a computer program designed to produce artificial point patterns that are spatially distributed in two dimensions similar to hardwood rootstocks in young pine plantations. A hardwood rootstock is defined as all stems of the same species originating from a common point in the soil. The program can be used to generate populations for testing various sampling methods of interest and may provide a basis for other studies dependent on hardwood spatial distribution in southern pine plantations.

No information was found in the literature describing the spatial pattern of hardwood rootstocks in southern pine plantations. Development of the hardwood rootstock generator consisted of two stages: 1) determination of the range of pattern of hardwood rootstocks in young pine plantations, and 2) development of a stand generator. Data gathered in loblolly pine plantations were used to modify a spatial point generator developed by Newnham (1968) to produce artificial hardwood rootstock populations similar to those observed in the plantations.

FIELD METHODS AND DATA ANALYSIS

Selection criteria for field measurement sites consisted of the following: 1) logging debris (root masses, tree trunks) was not piled, 2) pines were less than 7 years old, and 3) sites were at least 10 acres in size. Piling of debris might influence the resulting pattern of rootstocks. Competing vegetation control measures (such as herbicides) are usually applied by age 6. Nineteen sample pine plantations (where nursery-grown seedlings have been transplanted) or areas of plantations were selected in the lower Piedmont and upper Coastal Plain of Alabama and Georgia.

Forty to fifty sample points and ten to twenty one-hundredth-acre fixed area plots were randomly located within each plantation area. Minimum hardwood rootstock heights of 2 feet (ft) and 4.5 ft were set for areas with mean pine total heights of less than 4.5 ft and greater than 4.5 ft, respectively. Shorter hardwood rootstocks do not exert as much competitive stress. Only hardwood species considered to be arborescent (treelike, attaining an average height of 15 ft or greater at maturity) were measured. Total height (vertical distance from ground line to tip of tree) to the nearest 0.25 ft, species and two measures of crown diameter were recorded for each sample pine and hardwood rootstock. Crown diameter was measured from bud to bud. At each sample point, distance from the sample point to the nearest pine and nearest hardwood rootstock were measured.

Several indices quantifying spatial pattern have been developed (Pielou 1977). Some of the indices are based on the distance between two organisms (plant-to-plant) or distance between a randomly located point and the closest plant (point-to-plant). Pielou's nonrandomness index (PNI), a point-to-plant index, was recommended to quantify spatial pattern due to high relative accuracy, sensitivity, and simplicity (Payandeh 1970). The index is calculated using equation 1. The index equals 1 when the underlying point pattern is random, is less than 1 when point pattern tends to a regular (or lattice) structure, and is greater than 1 when point locations tend to aggregate (Mountford 1961; Pielou 1959). A standardized normal variate is used to test for significiant departures from a random pattern. Pielou's nonrandomness index was used in this study to quantify spatial pattern of both field and artificial sample populations.

$$PNI = PiWD \qquad (1)$$

where

PNI = Pielou's nonrandomness index
Pi = 3.141527 ...
W = Mean squared point-to-plant distance
D = Density of plants (number per unit area)

Pielou's nonrandomness index was calculated for both pine trees (PNIP) and hardwood rootstocks (PNI_h). Mean total height, density, and rootstock crown areas were calculated for each hardwood species or species group. Due to poor seedling survival in 1981, only one 5-year-old plantation was located. Table 1 contains descriptive information for each of the 19 study plantations.

The distribution function of total rootstock height was fit using a left- and right-truncated, two parameter Weibull function following the methods described by Zutter et al. (1982). Equations to estimate the cumulative frequency of crown area using age and total rootstock height were developed.

Mean pine density ranged from 389 to 1340 stems per acre and hardwood rootstock density ranged from 272 to 2120 rootstocks per acre (Table 2). Sample plot densities in excess of 4000 hardwood rootstocks per acre were encountered. The coefficient of variation (CV) for hardwood density ranged from 52.4% to 107.8% for plantations 3 and 13, respectively. The pattern of the planted loblolly pines in 17 of the pine plantations was determined to be significantly uniform at the 0.05 level and random in the remaining two plantations. In contrast, pattern of hardwood rootstocks was determined to be significantly uniform in five plantations and significantly aggregated in four plantations. The remaining 10 were judged to be random (Table 2). The only trend observed in PNI_h was the tendency of older stands (age 6) to be uniformly distributed. This may result from crown closure of the uniformly spaced pines creating uniform growing spaces for the

Table 1. Summary of sampled population characteristics.

Plantation number	Physiographic region[1]	Sampled acreage[2]	Age[3]	Site prep[4]
1	P	22.5	3	3
2	P	22.5	5	1
3	P	22.5	4	1
4	C	22.5	4	1
5	P	5.0	4	2
6	C	22.5	3	1
7	P	22.5	4	2
8	P	22.5	4	1
9	P	22.5	3	3
10	P	6.4	6	1
11	C	22.5	4	4
12	C	22.5	3	1
13	P	22.5	6	1
14	C	22.5	4	4
15	P	22.5	6	1
16	P	22.5	6	1
17	P	22.5	4	1
18	P	10.0	6	1
19	P	10.0	6	1

1/ P =lower Piedmont; C = Upper Coastal Plain.
2/ Acreage of area in which sample points were randomly located.
3/ Number of growing seasons since planting.
4/ 1 = chop and burn; 2 = shear and burn; 3 = shear, disk, and burn; 4 = double chop, burn, and chop.

hardwood rootstocks. Mean pine height in four out of the five uniform hardwood rootstock populations was significantly greater (p = 0.05) than mean hardwood rootstock height (Table 3).

Species composition was reasonably constant over all plantations. Table 4 lists all arborescent species encountered in ten or more plantations. Scatter diagrams of PNI_h versus relative density for each species and species diversity index illustrated no trend.

Table 2. Summary of pine stem density, hardwood rootstock density, and pattern values from sampled populations.

Plantation Number	Pine Stems Density[1]	Pine Stems PNI[2]	Hardwood Density[3]	Rootstocks PNI[2]
1	592	0.20+	683	2.45*
2	760	0.29+	1073	2.01*
3	800	0.40+	1360	1.98*
4	665	0.93	1300	1.55*
5	600	0.33+	682	1.23
6	1340	0.43+	1327	1.08
7	511	0.37+	528	1.02
8	790	0.28+	2120	0.96
9	635	0.21+	671	0.95
10	513	0.19+	900	0.87
11	558	0.25+	1174	0.86
12	1047	0.53+	1740	0.83
13	767	0.34+	500	0.79
14	712	0.32+	765	0.75
15	594	0.68	772	0.60+
16	552	0.31+	1433	0.54+
17	580	0.33+	1680	0.52+
18	389	0.20+	1000	0.49+
19	772	0.21+	272	0.47+

1/ Number per acre.
2/ Pielou's Nonrandomness Index: significantly aggregated at 0.05 level; + = significantly uniform at 0.05 level.

ORIGINAL VERSION OF NEWNHAM'S PATTERN GENERATOR

Newnham (1968) developed a program that produced a wide range of point patterns in a plane for use in tree harvesting simulation studies. The program requires two parameters for all point patterns - the dimensions of the area and the number of points to be generated (NPT). A minimum distance between points may be stipulated. Distance between each potential point and all previously allocated points is checked. The new point is rejected if the minimum distance criterion is not met. Assuming no rejections, the distance check routine in the original generator is performed ((NPT)(NPT-1))12 times. Pattern of clumps may be uniform, random, or clumped.

Uniform Patterns

Uniform patterns are produced by subdividing the area into equally sized cells and randomly locating the desired number of points per cell within each cell. Location of the point may be further restricted to a

Table 3. Mean pine and hardwood rootstock heights from sample plots.

Plantation number	age	Pine stems Mean height (feet)	Pine stems Sample size[1]	Hardwood rootstocks Mean height (feet)	Hardwood rootstocks Sample size[1]	t[2]
1	3	4.29	12	4.04	9	–0.74
2	5	6.65	15	6.60	13	–0.90
3	4	4.27	10	4.34	10	0.18
4	4	4.99	17	4.19	17	–1.92*
5	4	9.70	17	6.84	17	–3.36
6	3	2.83	16	4.48	16	4.66*
7	4	7.56	18	7.15	16	–0.74
8	4	3.70	10	3.84	10	0.41
9	3	3.96	17	4.27	16	0.81
10	6	11.42	15	6.99	15	–7.47*
11	4	5.45	19	7.00	19	5.18*
12	3	4.61	15	3.98	15	–1.71
13	6	9.46	18	6.82	16	–5.54*
14	4	6.15	17	6.25	17	0.21
15	6	11.34	18	6.64	17	–6.85*
16	6	8.82	21	6.98	21	–3.10*
17	4	4.40	10	4.32	10	–0.16
18	6	8.36	17	6.60	18	–2.18*
19	6	13.32	18	7.41	14	–7.86*

1/ Number of 1/100.acre circular plots.
2/ Calculated two-sided t-value for testing difference between pine and hardwood rootstock heights. * = significantly different at 0.05 level.

Table 4. Relative density of predominant species observed in field sample.

Species	Occurrence[1]	Relative Density[2] Mean[3]	Relative Density[2] Minimum[3]	Relative Density[2] Maximum[3]
Liquidambar styraciflua sweetbum	19	0.30	0.01	0.67
Quercus nigra, Q. phellos, waterwillow oak	19	0.17	0.01	0.44
Nyssa *sylvatica,* black tupelo	19	0.11	0.01	0.41
Cornus florida, dogwood	14	0.11	0.02	0.35
Carya spp., hickories	14	0.09	0.01	0.36
Liridendron tulipifera yellow-poplar	10	0.07	0.01	0.20
Diospyros virginiana, persimmon	18	0.06	0.01	0.12
Quercus spp. (subg, *Erythrobalanus*), red oaks	17	0.05	0.00	0.16
Prunus serotina, black cherry	16	0.05	0.01	0.12
Quercus spp. (subg. L*eucobalanus*), white oaks	14	0.04	0.02	0.09
Ulmus alata, winged elm	10	0.04	0.01	0.13
Sassafras albidum, sassafras	10	0.03	0.01	0.12

1/ Number of plantations in which species was present (19 possible).
2/ $\text{Relative Density} = \dfrac{\text{number of individuals of a species}}{\text{total number of individuals of all species}}$
3/ Values from plantations in which species occurred. Minimum values for all except *Nyssa sylvatica* are 0.00 if all plantations are considered.

subcell centered within the cell. Subcell size is specified as a fraction of cell side *(FRAC).* As this fraction approaches 0, a perfectly uniform pattern is produced. As the fraction approaches 1, a point may occur anywhere within the cell.

Random Patterns

Random patterns are generated by using a uniform pseudorandom number generator to produce X and Y coordinates.

Aggregated Patterns

Aggregated patterns are produced by locating a fixed number of clump centers *(NACL)* in a specified pattern and aggregating points around the clump centers. A point is randomly generated and the clump center nearest it is located. Assuming no point rejections, this routine is executed *((NPT)(NACL)(NACL-1))12* times. Distance from the generated point to the clump center is modified using equations 2 and 3 (Newnham 1968).

$$X_t = (X_r - X_c)rx^t \tag{2}$$

$$Y_t = (Y_r - Y_c)ry^t \tag{3}$$

where

X_t, Y_t are modified coordinates
X_r, Y_r are uniform random coordinates
X_c, Y_c are clump center coordinates
r_X, r_Y are uniform random numbers $(0 \, \Omega r \, \Omega 1)$
t is the transforming exponent

MODIFICATIONS TO NEWNHAM'S ORIGINAL GENERATOR

Random Number Generator

The distance check routine was eliminated and the random number generator was modified to produce integer numbers representing coordinates in tenths of feet (eg. 105 = 10.5 ft). The uniform random number generator can be generalized to produce coordinates that are any minimum distance apart by multiplying by the appropriate constant. Based on field observation, minimum distance between rootstocks for this study was set to 0.1 ft and clumps were randomly located.

Clumping Routine

In order to reduce time required to locate the nearest clump center, the coordinate plane was arbitrarily divided into 36 equal sized compartments. Clump centers were partitioned into sets corresponding to each compartment, and the clump center nearest to the generated point was located by searching the points compartment and adjacent compartments. Points falling in corner compartments required four compartment searches, edge compartments required six compartment searches, and interior compartments required nine compartment searches.

Pattern Control

In order to control the pattern of points using *PNI* as an input, aggregated and uniform point patterns were generated using Newnham's program. PTEST (Stauffer 1977) was used to estimate *PNI* from samples of size 100 until the coefficient of variation of *PNI* was less than or equal to 10%. Equations 4 and 6 were developed to predict generator inputs as functions of *PNI.*

Uniform Populations

Three hundred and sixty populations were generated using a range of values for total number of points and cell side fraction. Each combination was replicated at least twice and all populations were generated independently. Scatter diagrams revealed that total number of points had no effect on *PNI.* Equation 4 is used to predict cell side fraction as a function of desired *PNI* and accounted for 69% of variation in cell side fraction.

$$FRAC = 6.010202(\mathrm{PNI})^{0.5} - 4.189025 \tag{4}$$

where

FRAC = fraction of cell side length in which the generated point is restricted for uniform populations

PNI = Pielou's nonrandomness index

Aggregated Populations

Two hundred and thirty-two populations were generated using several levels of total number of points and a transforming exponent *(ATR).* A third variable, the number of points per clump *(PPCL),* was also used to produce the populations. Equation 5 illustrates the relationship among total number of points, number of clumps, and points per clump. As with uniform populations, total number of points did not have an effect on *PNI.* A quadratic response surface using points per clump and *PNI* was developed to predict the transforming exponent (eq. 6). Both the model and the individual parameter estimates were statistically significant ([Pr>F] < 0.0001 and [Pr>t] < 0.004, respectively) and explained 75.7% of the variation in the transforming exponent.

$$PPCL = NPT/NACL \tag{5}$$

$$\begin{aligned} ATR = {} & 0.013021\,(PPCL)^2 + 0.0001922975\,(PPCL)\,(PNI) \\ & - 0.0323864\,(PNI)^2 - 0.159326\,(PPCL) \\ & + 2.206772\,(PNI) - 0.82758 \end{aligned} \tag{6}$$

Random Populations

One hundred and sixty random populations were generated. The values of *PNI* estimated by PTEST ranged from 0.82 to 1.24. These fall within the 99% confidence interval for *PNI* (0.779 to 1.243) for random populations and a sample size of 100.

GENERATION Of ROOTSTOCK ATTRIBUTES

Total rootstock height *(THT)* and crown area *(CARER)* attributes are assigned after a point is located. *THT* is generated from a two-parameter, left-and right-truncated Weibulldistribution (eq. 7) and *CARER* is determined conditionzlly on *THT.*

$$THT = b[t/b)]^c - \ln[1-[1-\exp((t/b)^c - (T/b)^c)]CDEN]]^{[1/c]} \tag{7}$$

where

b, c = scale and shape parameters

t, T = left and right truncation points

CDEN = value of cumulative distribution function of THT $(0 \, \Omega CDEN \, \Omega 1)$

THT = total rootstock height

Total Rootstock Height

The parameters for the Weibull distribution were estimated from the field data for each age using the method of maximum likelihood. Frequency distributions were truncated on the left with minimum total rootstock height and on the right with maximum observed total height for each age. Table *5* contains the parameter estimates for the height distribution at each age. None of the observed distributions differed significantly from the fitted distributions using the Kolmogorov-Smimov Maximum Deviation Test (p = 0.05).

Table 5. Summary of left- and right-truncated, two-parameter Weibull distributions for total rootstock height.

Age	Weibull	parameters[1]	Maximum deviation[2]
	b	c	
3	4.5733	1.6592	0.0639
4	5.1188	1.7243	0.0726
5	2.5908	1.0748	0.0836
6	3.3960	1.2144	0.0796

1/ Parameter estimates of the left- and right-truncated Weibull distribution: b = "scale" parameter; c = "shape" parameter.
2/ Maximum deviation between observed and predicted proportions. Deviations not significant by Kolmogorov- Smirnov test.

Crown Area

The empirical distribution function for crown area was plotted by each age and total height combination. Crown area was regressed against its cumulative relative frequency of total rootstock height. Equation 8 is the general form of the model used. The parameter estimates (b_0 and b_1) were then regressed against total rootstock height. Equations 9 and 10 were highly significant and accounted for 85% and 66% of the variation and b_0 and b_1, respectively. The exponents for total rootstock height and its cumulative relative frequency were determined after examination of scatter diagrams.

$$CAREA = b_0 + b_1 (PERC)^5 \tag{8}$$

$$b_0 = 0.162712 + 0.027227(THT)^{2.5} \tag{9}$$

$$b_1 = -0.771563 + 0.953283 (THT)^{1.5} \tag{10}$$

where

CAREA = hardwood rootstock crown area
PERC = cumulative relative frequency of crown area
b_0, b_1, = parameter estimates

Stand Generation

Crown area and total rootstock height are generated as follows. Stand age, an input, determines the parameters of the Weibull distribution. A uniform random number, representing a value of the cumulative distribution function (cdf) of total rootstock height, is generated and the appropriate value of total rootstock height is determined (eq. *7).* Total rootstock height is used to determine bo and b, using equations 9 and 10. Another uniform (0,1) random number is generated and crown area is determined using equation 8. Figure 1 illustrates representative 3 year old and 6 year old crown maps. Note that stem location is identical.

GENERATOR PERFORMANCE AND VALIDATION

Point Generation Time

The mean time per point required by the modified generator was considerably less than that required by the original generator in most cases (Table 6). The decrease for total number of points greater than 100 is due to partitioning the clump centers. However, as the number of clumps per compartment increases, execution time will increase. If the number of clump centers per compartment is kept below 2000, this increase should be minimal. The processor times (based on CPU time required by an IBM 3033 mainframe computer) in Table 6 for aggregated populations were calculated assuming five points per clump and a transforming exponent of 2.0. The total cost to generate the specified number of points is based on a cost of $250 per processor hour. The modified generator should be faster than Newnham's original generator when total number of points exceeds 1000.

Pattern Control

Equation 4 was tested by generating 24 populations and comparing the estimated *PNI* with the desired *PNI* (Table 7). Positive values indicate the desired value exeeded the estimated value. The greatest difference was 0.1144, 14% of the desired *PNI*. Figures 2 and 3 illustrate the range of uniform patterns produced. While stem locations are a minimum distance apart, crowns will often overlap (Figure 4).

Figures 5 and 6 illustrate the range in clumped patterns that can be produced. Equation 6 was tested by generating 120 populations consisting of 40 combinations of points per clump and *PNI*. Table 8 contains the mean differences between the desired and estimated values of *PNI*. The greatest mean difference was 1.185, which is 50% of the desired value. However, the greatest difference below the inscribed line is -0.2113, or 13% of the desired value. Recall that the clump centers were randomly located. When number of points per clump is small, especially when equal to 1, the points tended to be randomly distributed. Thus the probability that a random point pattern will have *PNI* of 2.4 is infinitesimal. The line isolates the levels of points per clump for which desired values of *PNI* will not be attained but are probably of little practical significance anyway. Figure 7 illustrates the similarity between a random pattern and a clumped pattern with low density clumps.

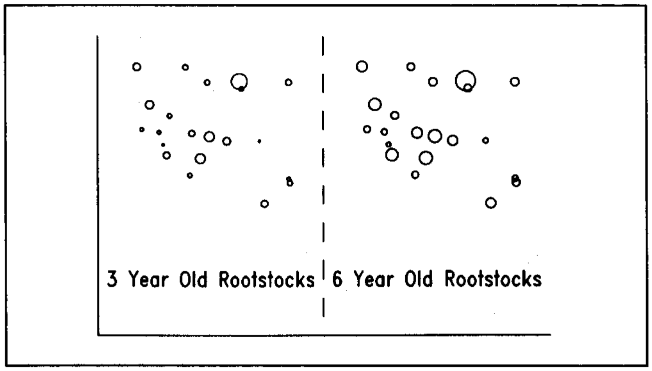

Figure 1. Simulated crown areas for three- and six-year-old hardwood rootstock populations (note that rootstock locations are identical).

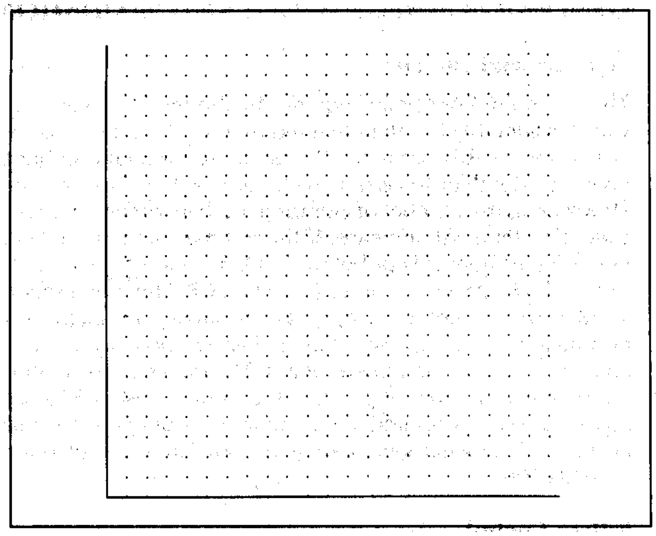

Figure 2. Simulated uniform rootstock population. Pielou's nonrandomness index (PNI) = 0.54, density = 518 rootstocks per acre.

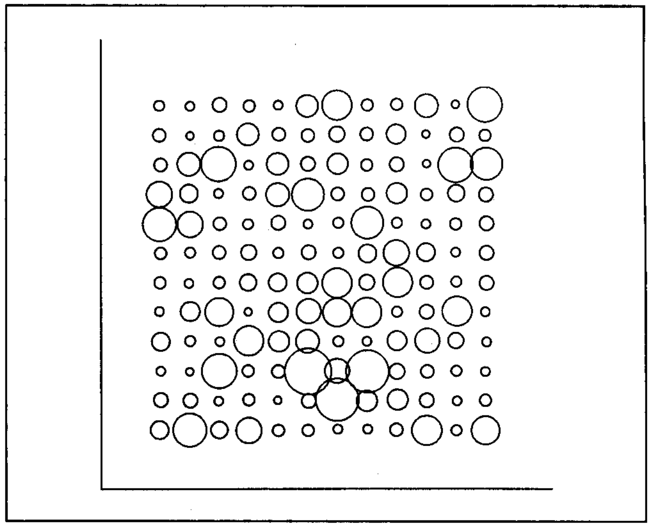

Figure 4. Enlargement of Figure 2 illustrating overlap of rootstock crowns.

Table 6. Performance of original and modified spatial point generators.

Patten Type	Points generated	Processor time[1]		Total cost[4]	
		Original[2]	Modified[3]	Original[2] ($)	Modified[3] ($)
Uniform	100	9.89	9.40	0.07	0.07
	1000	2.65	1.04	0.18	0.07
	5000	7.77	0.30	2.70	0.11
	10000	15.22	0.22	10.57	0.16
Random	100	10.00	1.30	0.07	0.07
	1000	2.74	1.03	0.19	0.07
	5000	8.53	0.29	2.96	0.10
	10000	16.86	0.20	11.71	0.14
Aggregated	100	9.72	12.90	0.07	0.09
	1000	3.40	1.96	0.24	0.14
	5000	11.64	1.71	4.04	0.60
	10000	23.04	2.61	16.00	1.81

1/ Time per point (X 10^{-3} seconds) using an IBM 3033 mainframe computer.
2/ Newnham's original spatial pattern generator
3/ Modified Newnham's generator
4/ Assuming $250 per processor hour.

Table 7. Ability of modified stand generator to produce point patterns with desired levels of Pielou's randomness index *(PNI)* for uniform populations.

Desired PNI	Number of Points Generated (NPT)		
	500	1250	2000
	(desired *PNI* – estimated *PNI*)		
0.50	-0.0658	-0.0187	-0.0446
0.55	-0.0551	0.0179	-0.0023
0.60	-0.0088	0.050 4	0.0105
0.65	0.0017	0.028 7	0.0095
0.70	-0.0133	0.0175	0.0325
0.75	0.0232	0.042 3	0.0034
0.80	0.1144	0.0612	0.0487
0.85	0.0489	0.0123	0.0922

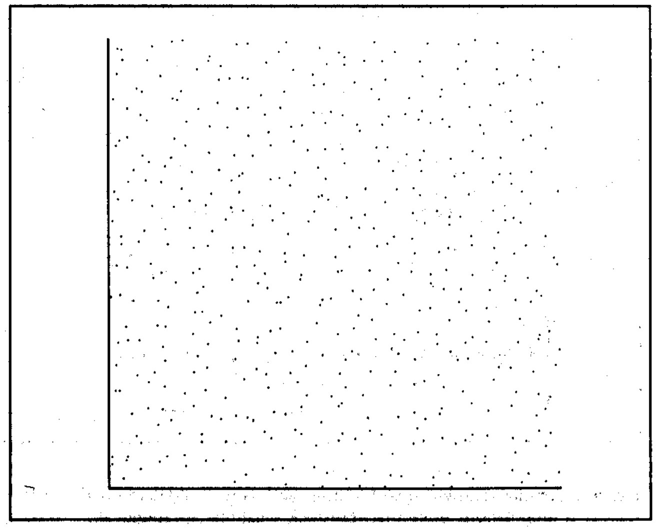

Figure 3. Simulated uniform rootstock population, Pielou's nonrandomness index *(PNI)* = 0.70 density = 504 rootstocks per acre.

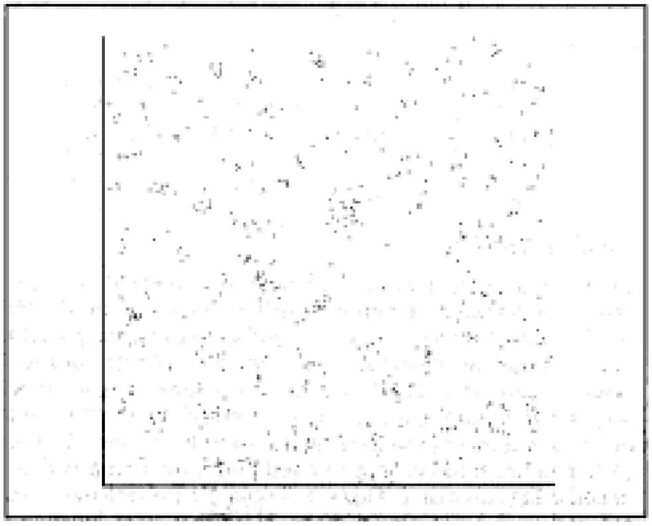

Figure 5. Simulated clumped rootstock population, *PNI* = 1.52, density = 500 rootstocks per acre.

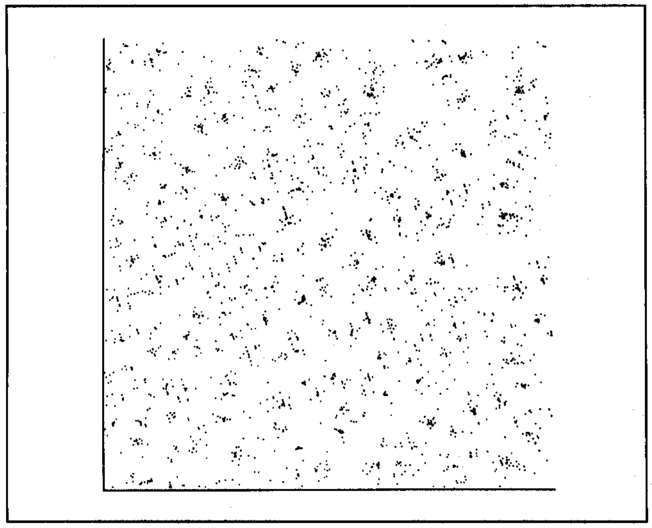

Figure 6. Simulated clumped rootstock population, PNI = 2.14, density = 2500 rootstocks per acre.

APPLICATIONS

The simulator can produce point patterns with a desired level of Pielou's nonrandomness index *(PNI)* with reasonable precision and then generate characteristics of hardwood rootstock stands similar to those found in young loblolly pine plantations. The required inputs for the simulator are: (1) size of the area to be generated, (2) number of points desired, (3) desired population pattern, and (4) age of the stand. Additionally, the mean number of points per clump is needed for aggregated populations with randomly located clump centers.

Due to the versatility of Newnham's original program, several types of point patterns could be produced. The modifications described in this paper significantly reduced execution time and thus facilitate use of the generator. The reduction in time requirements enabled the development of equations 4 and 6. Similar equations can be easily developed for other ecological indices. The methodology whereby an ecological index can be used to control the production of a point pattern both accurately and inexpensively has been demonstrated. Spatial pattern can be more easily incorporated into ecological models such as that developed by Wu et al. (1985).

The behavior of *PNI* and other indices as functions of the underlying point arrangements can be more fully examined. The development of new sampling methods and evaluation of existing methods can be conducted through simulation and reduce the need for costly field experiments. The effects of spatial pattern on sampling estimators can be examined without assuming explicit functions to describe pattern.

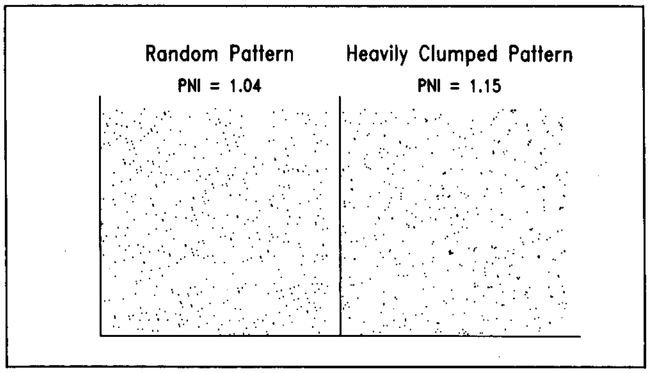

Figure 7. Comparison of a random rootstock population with a heavily clumped rootstock population having a mean of 1 rootstock per clump center.

One final area of application is in growth and yield modelling. The model SDPTAEDA (Daniels et al. 1979) is one example where wood volume production is affected by spatial arrangement of trees. As forest management activities continue to become more intensive, growth and yield models that economically provide information for decision making will need to become more detailed and realistic. Spatial pattern simulation can more easily be incorporated into such models.

Table 8. Ability of modified stand generator to produce point patterns with desired levels of Pielou's nonrandomness index *(PNI)* for aggregated populations.

Points per clump	Desired PNI 1.2	1.6	2.0	2.4
	(desired PNI – estimated PNI)			
1	0.035	0.38991	0.8172	1.1852
2	-0.0996	0.1949	0.3517	0.7635
3	-0.1318	-0.0363	0.2386	0.4419
4	-0.0354	-0.0520	0.0447	0.3102
5	0.0179	-0.0175	0.0926	0.1346
6	0.0300	-0.0295	-0.0414	-0.0156
7	0.0912	0.0573	-0.0271	0.0753
8	0.0850	-0.1073	-0.1362	0.1913
9	0.1066	-0.0375	-0.1175	0.0350
10	-0.0134	-0.2113	-0.0769	0.1145

1/ Probability of obtaining desired *PNI* for combinations of points per clump and desired PNI above line is essentially zero.

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