Selecting a sampling method to aid in vegetation management decisions in loblolly pine plantations[1]

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Objective methods to evaluate hardwood competition in young loblolly pine (*Pinus taeda* L.) plantations are not widely used in the southeastern United States. Ability of common sampling rules to accurately estimate hardwood rootstock attributes at low sampling intensities and across varying rootstock spatial distributions is unknown. Fixed area plot, polyareal plot, and Batcheler's triple-point distance sampling estimators of hardwood rootstock density, total height, and crown area were evaluated using computer simulation. Rootstock age, density, and spatial pattern combinations defined 24 artificial populations representative of hardwood rootstocks found in young loblolly pine plantations. Relative bias, relative precision, and within- and between-sample variance of the estimators were used as evaluation criteria. Eighteen sampling estimators with sampling intensities of approximately 1% were evaluated. Mean relative bias ranged from 1.2 to 7.0%, −1.5 to 1.0%, and −3.8 to 3.4% for fixed area, polyareal, and distance estimators, respectively. Spatial pattern affected evaluation criteria. Relative precision was highest in uniform populations and lowest in clumped populations. Variance was lowest in uniform populations and highest in clumped populations. Batcheler's distance estimator performed poorly. The 0.01-acre (1 acre = 0.405 ha) circular plot, vertical line, and horizontal point estimators were deemed "best" for density, total height, and crown area estimation, respectively. Vertical line sampling estimated all three attributes well and is recommended for field testing in young conifer plantations.

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Des méthodes objectives permettant l'évaluation de la compétition par les feuillus dans de jeunes plantations de pin à encens (*Pinus taeda* L.) ne sont pas d'usage courant dans le sud-est des États-Unis. La capacité des règles d'échantillonnage habituelles à estimer correctement le matériel feuillu sur pied demeure inconnue à de faibles intensités d'échantillonnage et pour une gamme de distributions spatiales. Des estimateurs de la densité des feuillus, de leur hauteur et de leur surface de cime, utilisant des parcelles à surperficie déterminée, à superficies multiples et la méthode d'échantillonnage à trois points de Batcheler ont été évalués à partir de simulations. Des combinaisons d'âge, de densité et de distribution spatiale ont permis de définir 24 populations artificielles représentatives du matériel feuillu rencontré dans les jeunes plantations de pin à encens. Le biais relatif, la précision relative de même que les variances intra et inter-échantillon des différents estimateurs ont été retenus comme critères d'évaluation. Dix-huit estimateurs échantillonnaux ont été comparés pour des intensités d'échantillonnage d'environ 1%. Le biais relatif moyen variait respectivement de 1,2 à 7,0%, −1,5 à 1,0% et −3,8 à 3,4% pour les estimateurs obtenus avec des parcelles à aire déterminée, des parcelles à aires multiples et pour ceux basés sur des mesures de distance. Les patrons de distribution spatiale ont influencé les critères d'évaluation. La précision relative était supérieure dans les populations uniformes et la plus faible dans les populations irrégulières. L'estimateur de distance de Batcheler a fourni de piètres résultats. Des parcelles circulaires de 0,01 acre, des estimateurs à partir de lignes verticales et de points horizontaux ont été considérés respectivement les meilleurs quant à l'estimation de la densité, de la hauteur totale et de la surface de cime. L'échantillonnage par lignes verticales a estimé les trois attributs correctement et est recommandé pour des essais sur le terrain dans de jeunes plantations de conifères.

[Traduit par la rédaction]

Introduction

It is often necessary to determine the amount of small woody vegetation found on a parcel of land. Such knowledge may be required by ecological studies. Planted loblolly pine (*Pinus taeda* L.) seedlings grow better in the absence of competing vegetation, as does any agronomic crop. Knowledge of the amount or level of hardwood vegetation in a young pine plantation is needed to evaluate site preparation effectiveness, determine the need for pine release, and provide input into growth and yield models such as the ones developed by Burkhart and Sprinz (1984) and Smith and Hafley (1987). The ability of field survey methods to estimate the amount of hardwood vegetation in young loblolly pine plantations has seldom been evaluated in the southeastern United States, particularly as a function of rootstock density and spatial distribution. The need for an objective, accurate method is critical, considering the costs of various cultural treatments associated with establishing and maintaining young pine plantations.

Several approaches may be taken in developing such a method. Various techniques can be field tested directly in a variety of stands and results compiled in a comparative format. This approach is time consuming though, particularly if several methods are tested and replicated over a wide variety of stands. In addition, the true population parameters for each stand are difficult to determine.

Another approach involves characterizing natural hardwood populations that exist in loblolly pine plantations, then developing a computer simulation model that reasonably

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reproduces artificial populations with similar characteristics. These generated populations can be sampled repeatedly by any number of desired techniques and the empirically derived sample estimates for each technique can be compared directly with known simulated population parameters. This paper describes the use of simulation to evaluate bias, precision, and variability of several sampling estimators of competing hardwood vegetation in young loblolly pine plantations at sampling intensities currently considered operational. With the exception of the distance estimator examined in this study, all other estimators are familiar to the forestry literature.

Literature review

Sampling estimators have been evaluated both analytically and empirically. Oderwald (1975) derived sample mean and variance formulae for plot and horizontal point estimators for populations with spatial patterns described by negative binomial, square lattice, and Poisson distributions. Density estimators were unbiased for all three spatial patterns but variances of basal area estimates derived from fixed and horizontal point samples increased as pattern changed from uniform to random to clumped (Sukwong et al. 1971; Oderwald 1981).

Early empirical work consisted of field sampling or sampling mapped stands (Grosenbaugh and Stover 1957; Lindsey et al. 1958). Horizontal point sampling was found to require about the same amount of time as 0.1 acre (1 acre = 0.405 ha) circular plots in a comparison using a mapped stand. The advent of computer simulation resulted in many empirical sampling studies. The effects of plot size, shape, and arrangement on density estimates have been examined (Kulow 1966). Plot sampling was found to be more efficient than horizontal point sampling for estimation of total frequency and less efficient for estimation of total volume and basal area (O'Regan and Palley 1965). In addition, horizontal point sampling estimates of frequency were found to be more variable than estimates of basal area and volume. In a separate study, variability of estimates of frequency was found to be equivalent to variability of estimates of basal area and volume for horizontal line sampling (Palley and O'Regan 1961). The cost effectiveness of circular plots and horizontal point sampling was also examined. Plot sampling was found to be more cost effective for estimation of frequency; point sampling was more cost effective for basal area estimation (O'Regan and Arvanitis 1966). Zeide and Troxell (1979) compared plot and point sampling using sampling efficiency and time spent per tree as criteria. Point sampling was found to be marginally more efficient.

Kaltenberg (1978) examined the effects of spatial pattern on stocking and density estimators in regeneration stands. Systematic sampling with a random start was simulated. Plot and vertical line and point estimators provided unbiased estimates of stocking for random and uniform patterns, and clumped patterns described by the Thomas series (Thomas 1949). Relative efficiency was defined as the trade-off between plot size and number of plots. Circular plot estimators were found to be more efficient than vertical point and line estimators. Gross et al. (1980) compared several distance, plot and point estimators of density, basal area, and proportion of cankered jack pine (*Pinus banksiana* Lamb.) and found only plot and point estimators were unbiased. A strip plot that sampled an average of 18 trees per point was judged to be the best rule. Payandeh and Ek (1986) also compared a circular plot estimator with five distance estimators. The circular plot estimator was unbiased for uniform, random, and clustered populations. Of the distance estimators compared, only a ratio of means estimator was unbiased for all three spatial patterns.

Weise and Glover (1987*b*, 1990) evaluated plot and polyareal estimators of density, total height, and crown area of hardwood rootstocks. Horizontal line sampling was recommended as the best estimator for field evaluation. Performance of polyareal estimators was superior to plot estimators owing to inequality in the average number of rootstocks sampled. Brown and Mugasha (1988) described a two-stage method to sample young forest stands. Vertical point sampling was used to select a preliminary sample in the field. Diameter and distance to the sample trees were recorded. A computational procedure identical to horizontal point sampling was then used to subsample the preliminary sample.

Persson (1971) reviewed density estimation using distance methods. Distance methods can be separated into two groups: those based on plant to plant distances and those based on sample point to plant distances. The distance estimators were divided into four types: (*i*) those based on the reciprocal of square of the mean distance; (*ii*) those based on the reciprocal of the mean of the squared distance; (*iii*) those based on squares of the reciprocal distances; and (*iv*) those based on the reciprocal of the square of the median distance (Warren 1971). Many of the estimators, designed to be unbiased for random spatial patterns, were biased for clumped or uniform patterns.

Several distance methods have also been examined in hopes of developing a method that provides unbiased density estimates (Diggle 1975; Warren and Batcheler 1979; Payandeh and Ek 1986). Most of the studies have simulated mature forests. Lyon (1968) evaluated the ability of 19 plot and distance methods to estimate bitterbrush (*Purshia tridentata* (Pursh) DC.) density using an 8 acre (3.24 ha) stand. The methods examined were not acceptable owing to the large sample required to obtain a precision of 50 plants (approximately 10% of the mean) per acre (124 per ha).

The distance estimator developed by Batcheler (Warren and Batcheler 1979) was developed using one point to plant and two plant to plant distances. The following distances are measured: sample point to nearest plant, first plant to nearest plant, and second plant to nearest plant excluding the first plant. The point to plant distances are used to initially estimate density. The plant to plant distances are used to adjust the initial estimate for clumping and clumping within clumping. Batcheler's method was compared with the standard New Zealand Forest Service plot method of inventory in pine plantations (Batcheler and Hodder 1975). Time required per sample of Batcheler's method was 1/28th that of the plot method; time required for Batcheler's method to achieve equal precision was about half that of the plot method.

Horizontal point sampling has been used with some success in shrub communities (Cooper 1963; Meeuwig 1981; Friedel and Chewings 1988). It has generally been the most time-efficient method. Selection probabilities for horizontal point and line sampling are functions of crown area and diameter. Cooper (1963) found that prism angle gauges were unsatisfactory for use in shrub stands as it was often difficult to visually distinguish individual crowns and that horizontal point sampling with prisms was "unworkable" when shrub cover exceeded 35%. An angle gauge made of wood or aluminum

TABLE 1. Parameters of the twenty-four 16-acre (6.48 ha) artificial populations of hardwood rootstocks used to evaluate sampling rules

		Rootstocks		Sum of total heights		Sum of crown areas	
Age[a]	Observed α[b]	No./acre	No./ha	ft./acre	m/ha	ft.^{2}/acre	m^2/ha
3	0.61	503	1242	2 466	752	2 000	186
6	0.61	502	1240	3 473	1059	3 632	338
3	0.61	1552	3833	7 620	2323	6 165	573
6	0.61	1552	3833	10 701	3263	11 141	1036
3	0.61	2590	6397	12 655	3858	10 168	945
6	0.61	2590	6397	17 872	5449	18 622	1731
3	1.00	500	1235	2 454	748	1 982	184
6	0.98	500	1235	3 469	1059	3 602	335
3	1.00	1500	3705	7 355	2242	5 927	551
6	1.01	1500	3705	10 323	3147	10 732	998
3	0.99	2500	6174	12 200	3720	9 869	917
6	1.00	2500	6174	17 219	5250	17 843	1659
3	1.56	500	1235	2 464	751	1 986	185
6	1.60	500	1235	3 475	1059	3 610	336
3	1.57	1500	3705	7 327	2234	5 821	541
6	1.55	1500	3705	10 305	3142	10 598	985
3	1.56	2500	6174	12 241	3732	9 838	914
6	1.55	2500	6174	17 233	5254	17 914	1665
3	2.08	500	1235	2 439	744	1 972	183
6	1.99	500	1235	3 470	1058	3 619	336
3	1.98	1500	3705	7 320	2232	5 926	551
6	1.99	1500	3705	10 326	3148	10 690	994
3	1.92	2500	6174	12 270	3741	10 006	930
6	1.92	2500	6174	17 279	5268	18 032	1676

[a]Years since planting.
[b]α, Pielou's nonrandomness index (Pielou 1977).

improved performance of horizontal point sampling (Cooper 1957, 1963).

The use of vertical line sampling in regeneration surveys has been described (Bickerstaff 1961; Beers and Miller 1976). In surveys in central hardwood understories, vertical line sampling provided results comparable with milacre plot surveys in one quarter of the time expended (Beers and Miller 1976). For a 45° vertical angle, a tree is sampled if the distance to the tree is less than the tree's height. Other selection rules for different vertical angles can be devised.

No studies of low intensity sampling simulating density, age, and spatial pattern representative of shrub stands or hardwood rootstock stands were found. Fixed area plot, polyareal plot, and Batcheler's triple-point distance estimators have not been directly compared at low sampling intensity. Very little information pertaining to the cost of conducting a field sample using these techniques is published; much of the information is cited above. This paper describes results of a simulation study designed to compare these methods at a sampling inten- that we believe represents currently acceptable operational levels.

Methods

Population simulation

A stand simulator was developed to produce artificial hardwood rootstock populations similar to those observed in 3- to 6-year-old loblolly pine plantations in the Piedmont and upper Coastal Plain of Alabama (Weise and Glover 1987*a*). A rootstock is defined as a single- or multi-stemmed woody plant with all stems obviously growing from the same root system. Multiple-stemmed rootstocks, branching at or below groundline, are common in site-prepared stands in the southern United States. Crowns of the simulated rootstocks were assumed to be circular. Total rootstock height was modelled with a two-parameter right- and left-truncated Weibull distribution. Simulated total height ranged from 2 ft. (0.61 m) to 20 ft. (6.1 m) and simulated crown area ranged from 0.3 ft.^{2} (0.03 m^2) to 135 ft.^{2} (12.4 m^2). Crown area was determined conditionally by total rootstock height (Weise and Glover 1987*a*). Rootstock population parameters were 16 acres (6.48 hectares (ha)) in size; target rootstock densities of low (500 per acre, 1235 per ha), medium (1500 per acre, 3705 per ha), or high (2500 per acre, 6175 per ha); target values of Pielou's (1977) nonrandomness index (α of 0.6 (uniform), 1.0 (random), 1.6 (light clumping), and 2.4 (heavy clumping); and 3 or 6 years since planting (Table 1). The stand simulator reliably generated the desired spatial patterns for all except the heavily clumped populations. Values of α in these stands were within 20% of the desired α. Exact population densities can be achieved for the random and clumped populations. Uniform populations are generated by creating a rectangular grid and locating a rootstock within each grid cell. Cell size was determined by dividing total population area by the number of desired rootstocks. The simulator is integer based so calculated cell size is rounded off resulting in a number of rootstocks greater than the desired number. The target ranges of density, α, and age were observed in the 19 plantations sampled to develop the simulator (Weise and Glover 1987*a*).

Sampling simulation

Plot centers were selected by simple random sampling and located anywhere within the simulated stand's boundaries. In the event that a plot overlapped a boundary, the opposite side of the stand was projected into the area of overlap (Wensel 1975). The following sampling rules were examined: fixed area plot, polyareal plot (horizontal point, horizontal line, vertical point, and vertical line), and Batcheler's triple-point distance methods (TPD) (Warren and Batcheler 1979). Ranked-set sampling (Dell and Clutter 1972), while

TABLE 2. Summary of sampling rules evaluated

Type	Code	Size or angle	Samples per acre	Length		Rootstocks sampled	
				ft	m	No./acre	No./ha
Circle	C1	0.010[a]	1[b]			15.4	38
	C2	0.004	2.5			15.7	39
	C3	0.002	5			16.1	40
Square	S1	0.010	1			15.0	37
	S2	0.004	2.5			14.8	37
	S3	0.002	5			14.7	36
Rectangle	R1	0.010	1			15.7	39
	R2	0.004	2.5			15.8	39
	R3	0.002	5			16.4	41
Horizontal point	HP	1000[c]	2.5			20.6	51
Horizontal line	HL	1000	1	25	7.6	13.3	33
Vertical point	VP1	30[d]	1			13.2	33
	VP2	45	2.5			11.0	27
Vertical line	VL1	60	1	50	15.2	11.6	29
	VL2	30	1	25	7.6	17.7	44
	VL3	45	1	25	7.6	10.2	25
	VL4	60	2.5	25	7.6	14.6	36
Batcheler's	TPD		5			15.0	37

[a] Plot size in acres.
[b] 1 sample/acre = 2.47 samples/ha.
[c] Crown factor (English units).
[d] Vertical angle in degrees.

theoretically unbiased and more efficient than simple random sampling, was not included in this study. The technique has been tested for forage and phytomass estimation (Halls and Dell 1966; Martin et al. 1980). However, ranked-set sampling is not widely known or used.

Plot sizes of 0.002, 0.004, and 0.01 acre (0.0008, 0.0016, and 0.004 ha) configured as circles, squares, and rectangles were tested using a 1% sampling fraction (nine sampling rules). Initially, horizontal point and horizontal line schemes were tested with tree crown factors (CF) of 100 and 200 at intensities of 1, 2.5, and 5 points (lines) per acre (2.5, 6.2, and 12.3 points (lines) per ha, 12 sampling rules). Crown factors are identical to basal area factors; a rootstock selected using a CF of 100 represents 100 ft.^{2} of crown area per acre (23 m^2/ha). Vertical point and line schemes were tested with vertical angles of 30, 45, and 60° at 1, 2.5, and 5 points (lines) per acre (18 sampling rules). Line samples were 50 ft. (15.2 m) long. On the basis of average number of rootstocks sampled by each scheme, the polyareal methods measured a much greater number of rootstocks than the other methods. To equalize the average number sampled, an additional CF of 1000 and a line length of 25 ft. (7.6 m) were added to the evaluation. Batcheler's method was also tested at 1, 2.5, and 5 points per acre (three sampling rules). Because of extreme inequality in average number of rootstocks sampled, 21 of the 60 sampling rules were eliminated from consideration. Of the remaining 39 sampling rules, the 18 rules closely approximating a 1% sample are evaluated in this paper (Table 2).

Vertical line sampling uses a vertical angle from the horizontal to select individuals. In this study, the vertex of the angle was located at ground level. When vertical line sampling is used in mature timber stands, the vertex of the angle is often at eye level. This practice results in the base of the angle being offset by the height of the observer's eye. This study simulated vertical line sampling as described by Bickerstaff (1961) and Beers and Miller (1976). Both sides of the line were checked for sample rootstocks instead of the single side described by Bickerstaff (1961). Crowns were projected to the ground for horizontal line and point sampling.

The relatively low sampling percentage (1% or 1, 2.5, or 5 sample points per acre) was chosen out of practicality in field application. Although greater sampling intensity should yield better results, the limitations of time and effort that would be expended in a field application of these techniques dictate relatively small samples. Hardwood crown diameter and cross-sectional area were used in this study rather than stem diameter and basal area because of relatively small stem sizes and the common problem of multiple stems for one hardwood rootstock in young pine plantations. Crown measurements are good indicators of competitive stress exerted on southern pines by hardwoods (Knowe 1991). Crown dimensions may also be measured feasibly from large-scale aerial photographs, thus reducing or eliminating field measurements (Smith et al. 1989).

Maximum distance travelled from the sample point to a rootstock was restricted to 50 ft. (15.2 m). This restriction applied only to the polyareal plot methods. Because these are p.p.s. (probability of selection proportional to size) methods, a large rootstock theoretically could be selected even though it was removed some distance from the sample point. Field sampling may fail to select this large individual because it is obscured by intervening vegetation. In practice, time and labor limitations also restrict the distance travelled from the sample point.

As each rootstock was selected, actual crown area and total height were tallied. Number of rootstocks, sum of total heights, and sum of crown areas were estimated for each sample. Standard errors of the estimates were calculated for all sampling methods except for Batcheler's TPD. The probable limit of error, an empirical analog to the standard error for a sample, was calculated for Batcheler's density estimates (Batcheler 1975). Sums of total heights and crown areas were estimated for TPD using eq. 1. Sampling ceased after the mean of all stand entry estimates for number of rootstocks did not differ by more than 0.5% for 10 consecutive stand entries or after 200 stand entries. A minimum of 10 stand entries was required.

$$[1] \quad \hat{Y}_{Bi} = \frac{\hat{D}_i}{3n} \sum_{j=1}^{n} \sum_{k=1}^{3} X_{ijk}$$

where $\hat{Y}_{Bi}$ is the ith sample estimate of variable of interest for Batcheler's TPD estimator (i = 1, 2, ..., m where m is the number of stand entries); $\hat{D}_i$ is Batcheler's TPD estimate of rootstocks per acre for ith stand entry; n is the sample size (16, 40, 80); X_{ijk} is the crown area or total height of kth rootstock at jth sample point.

Evaluation criteria

To evaluate the 18 sample rules, relative bias (RB) (eq. 2), relative precision (RP) defined as the percentage of estimates falling within ±5% of the true value, average variance, and variance between estimates were used (Schreuder and Thomas 1985). Because of the differing population densities, total height, and crown area distributions, average variance was expressed as the coefficient of variation ($\widehat{CV_A}$) (eq. 3); however, the actual per acre values (Y) were used in place of the estimated per acre values ($\hat{Y}$). Variance of each estimator is of interest for at least two reasons.

1. Given two estimators that are unbiased with respect to the same parameter θ and everything else equal, the estimator with the smaller variance is guaranteed to be "closer" to θ a higher fraction of the time in repeated sampling (Mendenhall et al. 1981).
2. Given the conditions in (1), the estimated sample size needed to achieve a desired allowable error is smaller for the estimator with the smaller variance.

Variance between estimates ($\widehat{CV_B}$) was defined as the ratio of the standard error between stand entry estimates divided by the actual population mean (eq. 4). Average variance describes the mean variation within a sample of 16, 40, or 80; $\widehat{CV_B}$ describes the variance between the m estimates. Variance between estimates was used as a proxy for consistency, a property of sampling estimators. Informally, a consistent estimator converges to the parameter θ as the sample size increases to ∞. From statistical theory, the variance of a consistent estimator goes to 0 as sample size increases to ∞ (Mendenhall et al. 1981). Thus $\widehat{CV_B}$ indicates relative consistency.

$$[2]\quad \mathrm{RB} = \left(\frac{\sum_{i=1}^{m}\hat{Y}_i}{mY} - 1\right)100$$

$$[3]\quad \widehat{CV_A} = \left(\frac{\sum_{i=1}^{m}\mathrm{SE}_i}{mY}\right)100$$

$$[4]\quad \widehat{CV_B} = \left(\frac{\sqrt{\dfrac{\sum_{i=1}^{m}(\hat{Y}_{.} - \hat{Y}_i)^2}{m(m-1)}}}{Y}\right)100$$

where $\hat{Y}_i$ is the ith sample estimate of the variable of interest, Y is the true population value of the variable of interest, SE_i is the standard error of the ith estimate, and $\hat{Y}_{.}$ is the mean of the estimates.

Mean values for each evaluation criteria were calculated across the 24 populations for density, total height, and crown area. Student's t-test was used to test if RB was significantly different from 0. Significance level for all tests was 0.05.

To select a single estimator that performed well across all 24 populations, each of the four criteria were ranked within a population. Ranks of the criteria were summed into composite scores for density (DSCORE), height (HSCORE), and crown area (CSCORE). Equal weighting was applied to each rank because we viewed all four criteria as being equally important. Other weighting schemes would have altered the results of this study. Mean scores for each sampling rule were calculated from the 24 population scores. Rank values ranged from 1 to 18, with 1 being best. Thus DSCORE, HSCORE, and CSCORE could range in value from 4 to 72. The best sampling rule, the rule with the lowest mean rank for DSCORE, was selected for each of the eight types of rules (circular, square, and rectangular plots, horizontal point and line, vertical point and line, and Batcheler's TPD).

Evaluation criteria for the eight rules were reranked by population, composite scores were calculated, and mean scores were computed and reranked as above. Rank values ranges from 1 to 8, with 1 being best. All performance criteria were plotted against spatial pattern. The sampling rule with the lowest mean score (mean of density, total height, and crown area scores) and with least sensitivity to changes in spatial pattern was identified as being the best rule of those compared.

Results

Relative bias

Mean RB (across 24 populations) ranged from −3.8 to 6.6%, −3.7 to 7.0%, and −3.4 to 6.7% for density, total height, and crown area estimates, respectively (Table 3). Mean relative bias was significantly different than 0 for most plot estimators (Table 4) and not significantly different for most polyareal estimators. Mean RB for the 0.01 circular (C1) and rectangular (R1) plot estimators was significantly different than 0 for only crown area and density, respectively. Relative bias of the 30° vertical line (VL2) estimator differed from 0 for density, crown area, and total height. Similarly, mean RB of the horizontal line (HL) estimator also differed from 0 for density and crown area. Relative bias of TPD estimates of density, total height, and crown area ranged from −3.8 to −3.4%. Mean relative bias of density, total height, and crown area estimators was 2.0, 2.1, and 2.1%, respectively. The variability among the 18 estimators in RB (represented by the CV) was an order of magnitude greater than the variability in the other performance measures (Table 3).

Relative precision

Mean RP ranged from 26 to 54%, 26 to 57%, and 21 to 59% for density, total height, and crown area estimators, respectively (Table 3). Batcheler's TPD consistently had the lowest mean precision of all estimators examined. If TPD is excluded, mean RP for most sampling rules was 40–50%. Mean RP was 42.7, 43.1, and 36.4% for density, total height, and crown area estimators, respectively.

Average variance and consistency

Average variance for all sampling rules except TPD ranged from 8.0 to 13.8% for density, from 9.4 to 11.5% for total height, and from 7.1 to 14.4% for crown area. Average variance for Batcheler's TPD, a function of the density estimate, was 21.6%. This is approximately twice the mean $\widehat{CV_A}$ for density (10.3%), total height (10.0%), and crown area (12.3%) of the other 17 sampling rules.

Variance between estimates ranged from 1.0 to 1.9% for density and total height and from 1.0 to 2.3% for crown area. The value of $\widehat{CV_B}$ for TPD, while double the minimum $\widehat{CV_B}$, was not twice the mean $\widehat{CV_B}$ of the other sampling rules. Mean $\widehat{CV_B}$ for crown area was significantly greater than total height $\widehat{CV_B}$ (pooled variance = 0.055 85, t = 3.93, df = 34) and density $\widehat{CV_B}$ (pooled variance = 0.081 85, t = 2.73, df 34).

Summary scores

Mean rankings of DSCORE, HSCORE, and CSCORE were determined for all 18 estimators (Table 5) The C1 estimator scores were ranked 1 for density, 2 for total height, and 7 for crown area. The 30°, 25 ft. VL2 estimator scores were ranked 2 for density, 1 for total height, and 3 for crown area. The HP and HL estimator scores ranked 1 and 2 for crown area,

TABLE 3. Mean values of relative bias (RB), relative precision (RP), average variance ($\widehat{CV}_A$), and consistency ($\widehat{CV}_B$) for 18 selected sampling estimators of rootstock density, sum of total heights, and sum of crown areas per acre in 24 simulated populations

Sampling rule	Density				Height				Crown area			
	RB	RP	$\widehat{CV}_A$	$\widehat{CV}_B$	RB	RP	$\widehat{CV}_A$	$\widehat{CV}_B$	RB	RP	$\widehat{CV}_A$	CV_B
C1	1.2	54	8.6	1.0	1.4	49	9.4	1.0	1.6	35	13.0	1.4
C2	2.2	50	9.6	1.2	2.6	45	10.3	1.3	2.9	32	13.7	1.9
C3	4.8	41	10.3	1.1	5.1	38	11.0	1.1	5.2	30	14.4	1.5
S1	2.8	50	8.9	1.2	3.3	45	9.7	1.3	3.6	34	13.2	1.8
S2	5.6	39	10.2	1.0	5.8	37	11.0	1.1	5.4	32	14.4	1.5
S3	4.5	41	10.2	1.0	5.0	39	11.0	1.1	5.3	29	14.4	1.5
R1	3.5	44	9.8	1.2	2.6	39	10.5	1.3	1.9	30	13.7	1.8
R2	5.4	41	10.1	1.0	5.8	38	10.8	1.1	5.8	30	14.2	1.4
R3	6.6	34	10.3	1.1	7.0	33	11.0	1.1	6.7	30	14.4	1.5
HP	0.8	4[illegible]	11.6	1.7	0.5	45	9.4	1.3	0.2	59	7.1	1.0
HL	0.7	47	9.9	1.5	0.5	51	9.1	1.4	0.5	48	9.5	1.4
VP1	0.4	40	12.2	1.7	−0.5	48	9.7	1.4	−1.5	43	10.3	1.5
VP2	−0.1	36	13.8	1.9	0.3	43	11.5	1.6	0.5	41	12.1	1.7
VL1	0.6	42	10.8	1.6	0.8	47	10.1	1.5	0.3	40	12.0	1.8
VL2	0.7	57	8.0	1.3	0.8	57	7.4	1.2	1.0	48	9.1	1.5
VL3	0.3	40	10.9	1.6	0.1	47	10.1	1.4	0.5	36	12.3	1.8
VL4	0.5	46	9.6	1.5	0.4	49	8.9	1.4	0.4	39	10.6	1.8
TPD[a]	−3.8	26	21.6	1.8	−3.7	26	21.6	1.9	−3.4	21	21.6	2.3
Mean	2.04	42.7	10.92	1.36	2.10	43.1	10.68	1.31	2.05	36.4	12.78	1.62
SD	2.61	7.2	2.98	0.31	2.76	7.4	2.91	0.21	2.78	8.9	3.09	0.26
CV	128	17	27	23	132	17	27	16	136	25	24	16

[a] CV_A is based on probable limit of error (Batcheler 1975) calculation which is a function of density. Sum of total rootstock heights and sum of crown areas are estimated from the density estimate so CV_A is identical for all three attributes.

TABLE 4. Summary of t-tests used to test significance of RB of 18 sampling estimators of density, sum of total rootstock heights, and crown area

Sampling rule	Density		Total height		Crown area	
	t^a	$p>\lvert t\rvert^b$	t	$p>\lvert t\rvert$	t	$p>\lvert t\rvert$
C1	1.492	0.1492	1.769	0.0902	2.100	0.0469
C2	6.936	0.0000	8.430	0.0000	8.446	0.0000
C3	5.619	0.0000	5.928	0.0000	5.521	0.0000
S1	3.079	0.0053	3.505	0.0019	3.376	0.0026
S2	7.201	0.0000	7.112	0.0000	7.230	0.0000
S3	6.860	0.0000	7.077	0.0000	7.444	0.0000
R1	3.880	0.0008	1.546	0.1358	0.823	0.4189
R2	5.707	0.0000	6.282	0.0000	6.061	0.0000
R3	7.390	0.0000	8.083	0.0000	7.775	0.0000
HP	1.824	0.0811	1.468	0.1555	0.722	0.4776
HL	2.331	0.0289	2.066	0.0503	2.077	0.0492
VP1	1.479	0.1528	−0.396	0.6954	−0.765	0.4520
VP2	−0.272	0.7881	0.837	0.4110	1.965	0.0616
VL1	1.230	0.2065	1.790	0.0866	0.489	0.6297
VL2	2.539	0.0183	2.642	0.0146	2.460	0.0218
VL3	0.535	0.5977	0.305	0.7630	1.009	0.3236
VL4	1.130	0.2700	0.990	0.3326	0.920	0.3669
TPD	−2.721	0.0122	−2.603	0.0159	−2.511	0.0195

[a] Value of Student's t-test.
[b] Probability of a greater t value (two-talied).

TABLE 5. Ranking of mean scores of 18 selected sampling estimators of rootstock density (DSCORE), total height (HSCORE), and crown area (CSCORE)

Estimator	DSCORE		HSCORE		CSCORE	
	Score	Rank	Score	Rank	Score	Rank
C1	16.65	1	22.33	2	32.04	7
C2	29.90	4	38.25	10	45.92	12
C3	41.31	12	45.98	13	48.58	15
R1	36.58	7	41.98	12	44.17	11
R2	40.98	10	46.00	14	48.33	13
R3	47.54	16	51.35	17	51.67	17
S1	25.35	3	33.29	7	40.65	10
S2	43.13	15	47.98	16	48.35	14
S3	40.73	9	46.65	15	50.96	16
HP	41.21	11	31.79	5	11.13	1
HL	33.67	6	28.21	4	21.08	2
VP1	42.13	13	31.94	6	25.65	4
VP2	50.60	17	41.67	11	30.67	6
VL1	40.50	8	35.31	9	32.54	8
VL2	18.79	2	17.17	1	23.02	3
VL3	42.21	14	34.19	8	36.98	9
VL4	31.40	5	26.67	3	30.42	5
TPD	61.33	18	63.25	18	61.85	18

NOTE: Lower values indicate better performance.

respectively. The 0.01 acre square plot (S1) estimator score ranked 3 for density. Batcheler's TPD scores consistently ranked 18 (or poorest) for density, crown area, and total height.

Based on the lowest average ranking, the 0.01 acre plots (C1, R1, and S1) and 30° vertical point (VP1) and VL2 were selected for final comparison with the HP, HL, and TPD estimators (Table 6). In this ranking, the vertical line estimator's mean score was lowest (2:00); VL2 ranked 1 for total height, 2 for density, and 3 for crown area. Circular plot and horizontal line mean scores were 2.67 and 3.00. Mean score of the horizontal point estimator was 4; the rank of HP

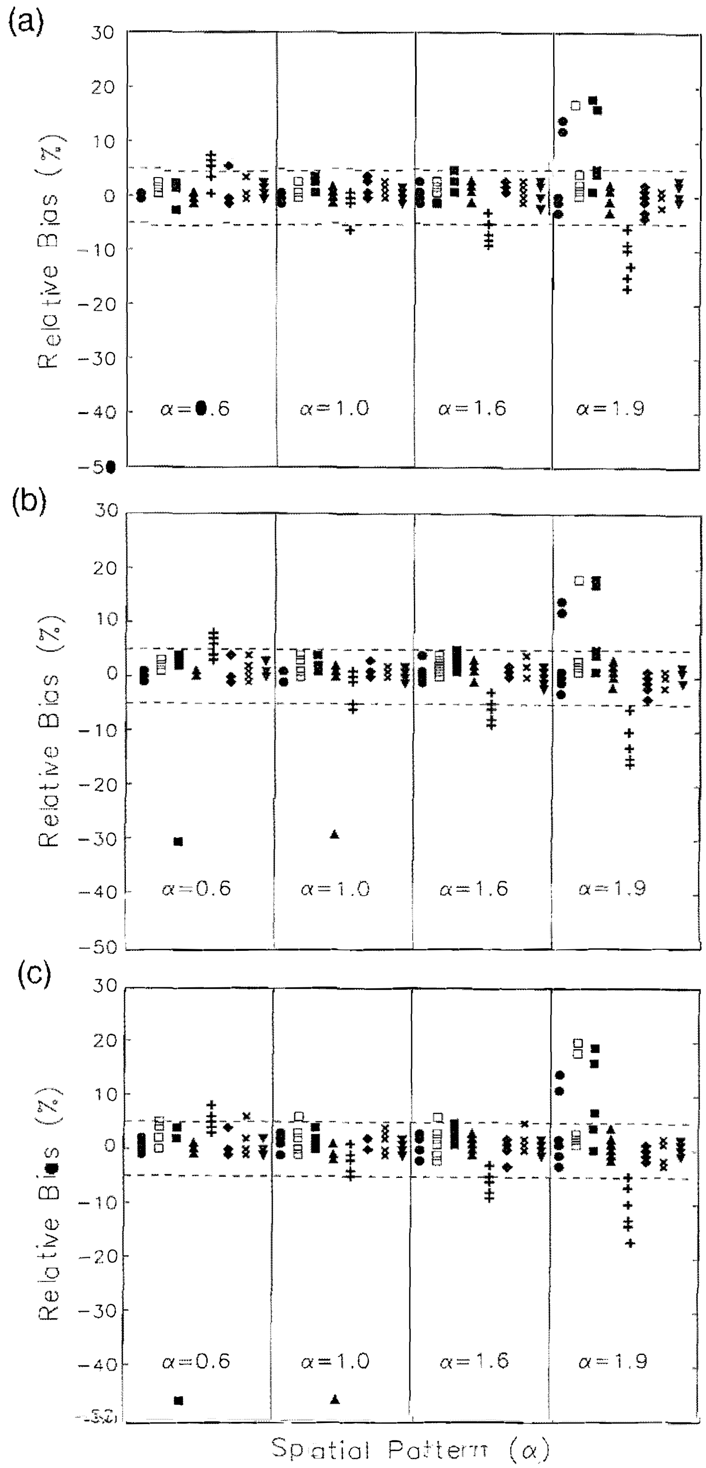

FIG. 1. Effect of spatial pattern on the relative bias of eight selected sampling estimators of number of rootstocks (*a*), sum of total rootstock heights (*b*), and crown area (*c*) per acre. ●, C1; □, S1; ■, R1; ▲, VP1; +, TPD; ◆, HP; ×, VL2; ▼, HL. Broken lines indicate ±5% relative bias.

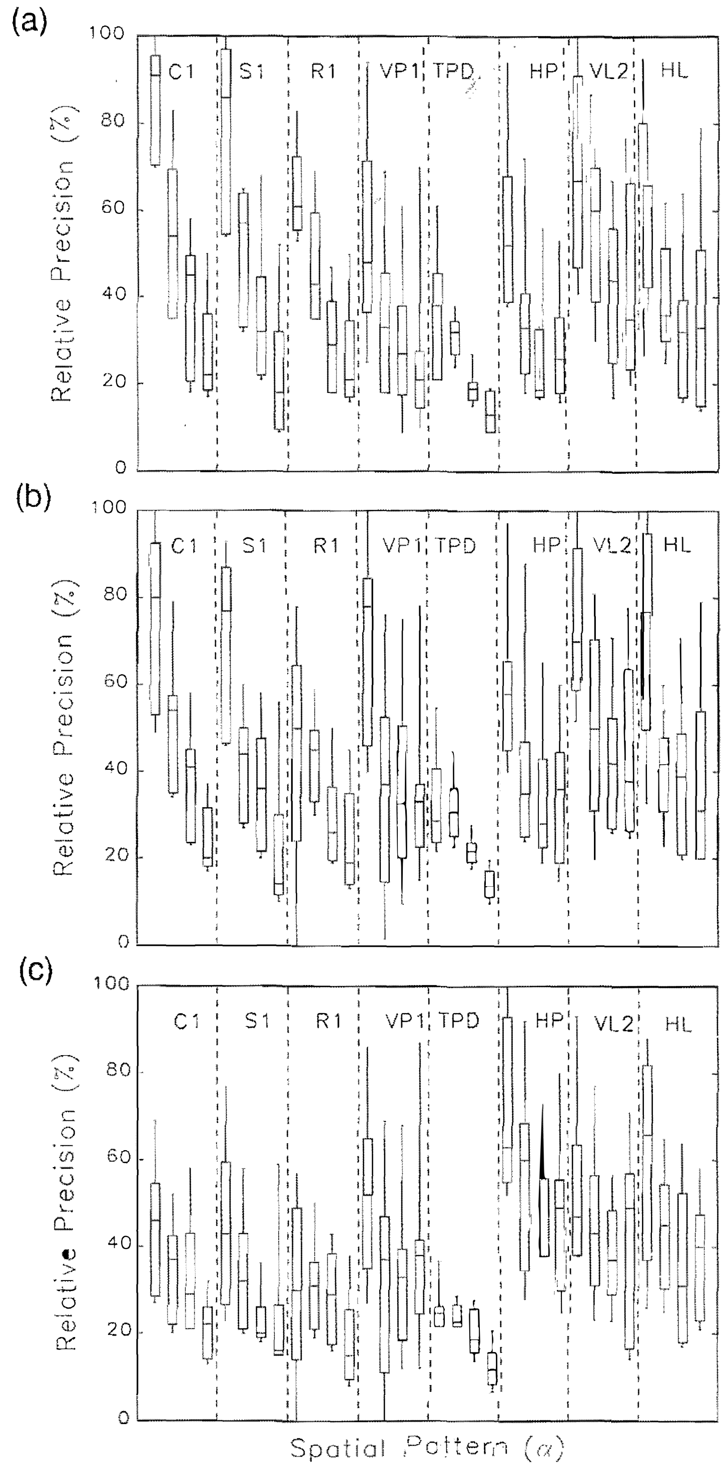

FIG. 2. Effect of spatial pattern on the relative precision of eight selected sampling estimators of number of rootstocks (*a*), sum of total rootstock heights (*b*), and crown area (*c*) per acre. For each estimator, α = 0.6, 1.0, 1.6, and 1.9 (left to right). Horizontal line in box is the median and whiskers indicate minimum and maximum relative precision for each spatial pattern class of six artificial populations.

for crown area was 1. The C1 estimator ranked 1 for density. Batcheler's TPD estimator's scores ranked poorest for all three population attributes.

Relative bias of most estimators was within ±5% for most populations (Fig. 1). Relative bias of Batcheler's TPD estimates of density, height, and crown area were all affected by spatial pattern. This results from the fact that crown area and height estimates are derived from the density estimate. The TPD estimator tended to overestimate in uniform stands and

TABLE 6. Ranking of mean scores of eight selected sampling estimators of rootstock density (DSCORE), total height (HSCORE), and crown area (CSCORE)

Estimator	DSCORE	HSCORE	CSCORE
C1	1	2	5
R1	5	7	7
S1	3	6	6
HP	6	5	1
HL	4	3	2
VL2	2	1	3
VP1	7	4	4
TPD	8	8	8

NOTE: Lower values indicate better performance.

underestimate in clumped stands (Figs. 1*a*–1*c*). In most cases, RB was less than 10% for most estimators in all but the heavily clumped stands ($\alpha = 1.9$). The RB of the R1 and VP1 estimators of total height and crown area in one uniform (density = 1552) and one random (density = 500) population were approximately −30 and −45%, respectively (Figs. 1*b* and 1*c*). The 0.01-acre plots (C1, R1, and S1) overpredicted by 10 to 20% in the two heavily clumped, 1500 rootstocks per acre populations. This may be partially due to improper plot size relative to clump size. With the exception for the VP1 estimator noted above, RB of the polyareal estimators (HL, HP, VL2, and VP1) was relatively stable across all spatial patterns.

Relative precision of all estimators was noticably affected by spatial pattern (Fig. 2). The box and whisker plots indicate the minimum, maximum, and median RP values by spatial pattern for each estimator. All six artificial populations within a pattern type were used to derive the values. The median is indicated by the horizontal line in the box. For an estimator, the pattern classes are (from left to right) $\alpha = 0.6$, 1.0, 1.6, and 1.9. Relative precision was highest in uniform populations and lowest in heavily clumped populations. The range in RP for most estimators was approximately 40%; the range of RP for the TPD estimator was generally lowest.

Spatial pattern affected both the average variance and consistency of all estimators. Average variance of the estimators was lowest in uniform populations and highest in clumped stands (Fig. 3). The range in variance increased as stands became more clumped. As noted above, TPD average variance was highest. Consistency ($\widehat{CV}_B$) exhibited the same trends as $\widehat{CV}_A$; however, TPD consistency was not highest.

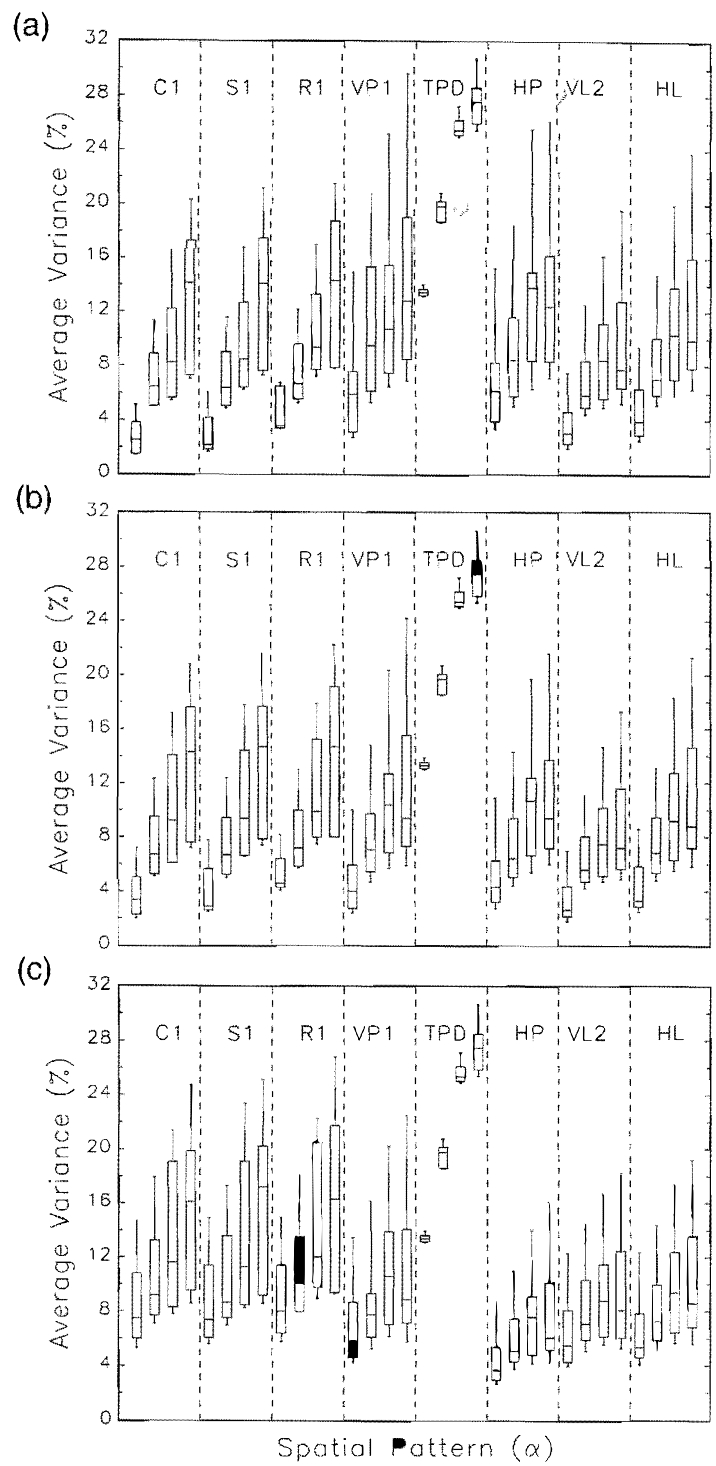

FIG. 3. Effect of spatial pattern on the average variance ($\widehat{CV}_A$) of eight selected sampled estimators of number of rootstocks (*a*), sum of total rootstock heights (*b*), and crown area (*c*) per acre. For each estimator, $\alpha = 0.6$, 1.0, 1.6, and 1.9 (left to right). Horizontal line in box is median and whiskers indicate minimum and maximum average variance for each spatial pattern class of six artificial populations.

Discussion and recommendations

Virtually all fixed area and polyareal plot estimators are relatively unbiased ($|RB| < 5\%$) at low sampling intensities except in heavily clumped stands. In this study, fixed area and polyareal plot estimators were unbiased as a group across the range of spatial patterns. We made no distributional assumptions describing rootstock location. Spatial pattern, rootstock density, and rootstock age affected all estimators. Batcheler's TPD estimator was strongly influenced by pattern. Increasing the number of rootstocks sampled could have improved the performance of all sampling estimators. By increasing the number of sample points or plots, RB and $\widehat{CV}_B$ will decrease to 0; RP and $\widehat{CV}_A$ will stabilize at the population constants. Changing plot size, vertical angle, or crown factor will simply change the number of rootstocks sampled. If plot size does not exceed clump size, then the performance criteria may not improve.

Fixed area plots have several desirable attributes. The estimator is unbiased. Plot boundaries facilitate selection of sample hardwood rootstocks and thus are "workable" in dense stands. However, density estimates are affected by plot size when spatial pattern is nonrandom (Pielou 1977). Increasing plot size reduces the effects of spatial pattern on relative precision, variation, and consistency. Achieving this reduction may be impractical as time per sample point increases accordingly. For example, an average of 50 rootstocks would be sampled at each sample point for 0.02-acre (0.008-ha) plots in stands with 2500 rootstocks per acre (6175/ha). In this study, 0.01-acre (0.004-ha) plots generally were the least biased, most precise, and least variable of the plot methods; however, 0.01-acre plots were affected by spatial pattern.

No single estimator was found to be the superior estimator of density, sum of total rootstock heights, and crown area per acre. If the objective is simply to estimate hardwood rootstock density, then 0.01-acre (0.004 ha) circular plots should be considered. Similarly, if the objective is to estimate the sum of rootstock heights or crown area, then vertical line sampling and horizontal point sampling should be considered. If the objective is to estimate all of these attributes with a single sampling estimator, then vertical line sampling should be considered. In this study, relative bias was less than 1%, relative precision was highest (57%), and within- and between-sample variances were low.

Rootstock crowns were assumed to be circular for this study. In reality, crown shape ranges from circular to elliptical to linear. This eccentricity in cross-sectional shape can affect polyareal sampling estimators (Grosenbaugh 1958; Biging and Wensel 1988). Bias can become a problem if correct formulae are not used to calculate crown area. This bias is a potential weakness of horizontal point sampling.

Wensel and John (1969) developed a method to combine fixed plot and horizontal point sampling into a single inventory. Such an inventory draws on the relative strengths of each estimator. This approach could be used to estimate rootstock density and crown area. Similarly, an inventory that used fixed area plots combined with horizontal point and vertical line sampling could be developed.

Hardwood rootstock attributes were used in this study to simulate existing conditions in young loblolly pine plantations. Performance of the sampling estimators is relative to these simulated attributes. Vertical line sampling has been used to estimate stocking of young stands in other regions of the United States. Species composition, density, and pattern differ in conifer plantations in the United States; however, the sampling rules are invariant. A wide range of stand conditions were simulated in this study so the results should be applicable in many different woody vegetation management decisions.

The use of vertical line sampling to provide information about the level of competing woody vegetation in conifer plantations is promising. The method is accurate, efficient, and objective; however, field testing of this method is needed. In a single comparison of vertical line sampling with 0.001 acre (0.0004 ha) plots, vertical line sampling produced "comparable" results with one quarter of the time expenditure (Beers and Miller 1976). Field tests will illustrate the practicality of the method as well as aid in equipment development and cost comparison. Once this testing is completed, the subjectivity that is now often required in plantation evaluation will be greatly reduced.

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