PRACTICALITY OF 3P SAMPLING WITH ACCURATE DENDROMETRY FOR THE PRE-HARVEST INVENTORY OF PLANTATIONS

K. H. LEE

Korean Forest Research Institute,
Seoul 130-012, Republic of Korea

and C. J. GOULDING

New Zealand Forest Research Institute,
Private Bag 3020, Rotorua New Zealand

(Received for publication 18 September 2000; revision 1 August 2002)

ABSTRACT

Conventional sampling schemes using bounded or point plots in a woodlot or stand of small area require a high proportion of the trees to be measured when recoverable (merchantable) volume is being estimated to the degree of precision normally required. Where the cost is high relative to the value of the woodlot, too few plots may be established to obtain useful confidence intervals and the trees within the plots themselves may be assessed too quickly for the predictions to be accurate. Individual tree sampling is often preferred over plot-based schema. PhotoMARVL, a method based on photographic image analysis of the stem, was developed to improve the accuracy of measurement over existing visual systems, but significantly adds to the cost of conventional pre-harvest inventory. Sampling with probability proportional to prediction (3P sampling) can efficiently utilise a more accurate though more costly measurement method such as PhotoMARVL. Additionally, it is useful where the stocked area of a woodlot is uncertain, as all the trees are visited and counted. In this study, 3P sampling was evaluated using pre-harvest inventory data of rotation-age *Pinus radiata* D. Don in New Zealand in order to test under what circumstances this system could be cost effective.

Where individual trees were visually assessed for diameter at breast height 1.4 m (dbh) to obtain a quick estimate of recoverable volume and a subsample was more accurately measured for product volumes using the conventional MARVL cruising technique, 3P sampling was the most cost-effective technique for woodlots of 5 ha or less. In less than a day a two-person crew could estimate the potential recoverable volume by broad log-product classes to within 10% of the mean. As the variability of a stand increased, or as the requirements for precision increased, the size of the area below which 3P sampling was competitive increased to between 20 and 40 ha. The coefficient of variation of the ratio of the quickly estimated volume to the MARVL measured recoverable volume is likely to be between 15 and 20%, across all tree sizes, independent of the variability of tree size. Utilising PhotoMARVL on a small subsample of trees within the woodlot would improve the accuracy of any value estimate and add the cost of approximately 4 person-hours. For larger areas, Point-3P sampling could be applied, but the combination with PhotoMARVL would increase costs by 60–70% over conventional double sampling with MARVL alone.

Keywords: dendrometry; pre-harvest inventory; 3P sampling.

INTRODUCTION

In general, an inventory should be accurate (unbiased), with the most precision (narrowest confidence intervals around the estimates) at least possible cost. However, there is a trade-off between more precision obtained with more measurements and cost, and higher times and costs to obtain more accurate measurements. The Method for the Assessment of Recoverable Volume by Log-types (MARVL) has been used as a standard pre-harvest inventory system in New Zealand since it was introduced by Deadman & Goulding (1979). There is increasing interest in obtaining estimates of the recoverable (merchantable) volume by log grades that are accurate, precise, and obtained at economic cost for stands with small areas and for woodlots (*see* Maclaren 2000). Conventional sampling with plots requires a high percentage of the trees of such stands to be measured at a corresponding high cost, unless the measurement of the trees is carried out quickly.

The field procedure of the MARVL system is a cruising system, where a sample of the standing trees is measured and their stem qualities are assessed visually. MARVL recognises the potential of a stand to yield different products when different log cutting (log merchandising or bucking) strategies are used in order to recover the optimal value from each stem. However, visual estimates of upper stem diameters, branch diameters, stem sweep, and the points at which changes in stem quality occur, may cause the system to give less accurate estimates of the value of individual trees than a system based on actual measurements. It is essential that field crews be well trained in MARVL dendrometry to use the system effectively (Hammond 1995; Goulding & Lawrence 1992).

When the area of a woodlot or stand is small, one solution is to base the sampling unit on the individual tree, with the total population defined by a complete count of trees, and to measure the sample trees more accurately. PhotoMARVL, a dendrometry system using photogrammetric techniques to analyse stereo images of photographs taken from the ground (Murphy 1998; Firth *et al.* 2000), provides accurate measurements on individual tree stems, especially the lower, more valuable 20 m of the stem. Heights of features up the stem can be obtained with an error of less than 10 cm, and stem and branch diameters can be measured to better than ±1 cm. A reliable 3D measure of stem sweep can also be provided. The system has other advantages such as providing the information without the tree being felled and providing a permanent photographic record enabling re-analysis should the log quality specifications alter. However, it requires more time in preparing data for calculating recoverable volumes than the standard MARVL system. In this paper recommendations are made for developing sampling procedures based on individual trees and the trade-off between the increased cost of measurement against the improved accuracy of PhotoMARVL.

In the MARVL system, a wide range of sampling options is available: simple random sampling or stratified sampling, with or without double sampling. The types of plots that can be used include bounded plots, point samples, horizontal-line plots, or single-tree sample units. Double sampling, with a combination of fully measured plots and "tally" plots measuring only basal area, is a popular option (Goulding & Lawrence 1992). This takes advantage of the generally good correlation between recoverable volume and basal area per hectare. Both Rayonier NZ Ltd and Fletcher Challenge Forests Ltd use a double sampling scheme with equal numbers of bounded plots and point samples. In the majority of MARVL inventories carried out by New Zealand companies, the sampling unit is a plot. If typical industry sampling intensities were followed, less than six plots would be established in a 4-ha woodlot —well below the number required to give the desired precision.

Sampling with Probability Proportional to Prediction (3P sampling) uses an individual tree as the sampling unit rather than a cluster of trees. 3P sampling was originally designed by Grosenbaugh (1965, 1967) for a timber sale inventory of a small area where each tree could be visited and their recoverable volumes predicted quickly and consistently by the cruiser. The central idea is to first make predictions for all trees (which greatly helps to improve the precision) and then measure some of the trees carefully (which eliminates any bias in the prediction phase). The accuracy of the cruise depends on the quality of the measurements of sample trees. Accurate dendrometry of a tree is important in this sampling method which could thus take advantage of the improved accuracy but high cost per tree of measurements by PhotoMARVL. Because all the trees are estimated, the sum of the estimates has no sampling error. 3P sampling has some disadvantages. The estimator is biased, though this bias is kept small, and only approximate calculations of sampling error can be made. The sample size is unknown prior to the field work being carried out. Despite these disadvantages, it is one of the new breed of modern, efficient, sampling methods (Iles 1995). It has been proven to be a very efficient method through field tests (Johnson *et al*. 1967; Bonner 1972) and theoretical study (Van Deusen 1987). 3P sampling has found its greatest application in an inventory situation where there are relatively few stems in the population and each individual tree is of relatively high value or each stem is utilised for several different products (Avery & Burkhart 1994). However, the necessity to visit all trees causes costs to rise in larger areas. In the future, with the use of remote sensing for automated tree counting (Goulding *et al.* 2000) this may become practical, but for the present it is difficult to justify using 3P sampling on areas over about 10–15 ha (K.Iles unpubl. data).

As an efficient sampling scheme for large areas, Grosenbaugh (1971, 1974) introduced Point-3P sampling, which is two-stage sampling with point samples in the first stage and a 3P subsample in the second stage. Each tree selected by the point sample ("in" trees) is assessed quickly for the 3P variable (usually individual tree height) and then 3P subsamples are selected from these "in" trees for careful measurement of the variables of interest such as recoverable volume. It takes advantage of point sampling, which does not involve visiting each tree and where trees are selected with probability proportional to their basal area, a good predictor of volume. The theory has been discussed by Schreuder, Brink, Schroeder, & Dieckman (1984) and Schreuder, Ouyang, & Williams (1992). It has proved to be a very efficient sampling scheme for large areas through field trials (Steber & Space 1972; Stamatellos 1995) and simulation studies (Mackisack & Wood 1990). Sampling error in Point-3P sampling arises from the sampling error of the plot samples plus the sampling error of the 3P individual tree samples. There is no upper limit on the size of the area on which it might be used. Steber & Space (1972) gave a sampling error of 7.1% of which 6.95% was attributable to the first stage sample alone. It is being used in Australia as well as in the United States, but has not been tried in New Zealand.

The aim of this study was to suggest effective sampling strategies using standard double sampling, 3P sampling, and Point-3P sampling for the estimation of recoverable volume by log types in the pre-harvest inventory of *P. radiata* plantations in New Zealand. To do this, different population sizes (areas) were simulated, varying levels of coefficient of variation between sample units in conjunction with varying levels of the desired percentage confidence intervals for the different sampling methods. The sample and work-study data on which the simulations were based were obtained from three existing sources. Specific objectives of the study were to:

- Examine the sample size requirements and cost (time) efficiency,
- Identify the practical factors and the barriers for practical application of 3P and Point-3P sampling, and
- Develop cost-effective methods of utilising an intensive measurement technique such as PhotoMARVL in combination with other sample measurements.

No attempt was made to determine the level of improvements in accuracy of PhotoMARVL over MARVL. Improvement in the precision of measurement could very well be associated with improvements in tree dendrometry, perhaps reducing the variation found in the study.

DATA

This study used data collected previously. PhotoMARVL dendrometry data were from young (12 to 15 years), unpruned, unthinned stands with a stocking of 500 stems/ha, owned by Carter Holt Harvey Ltd. Data from MARVL operational inventories of Rayonier NZ Ltd and a 100% measured "pilot" pre-harvest inventory in a single stand in Whakarewarewa Forest of Fletcher Challenge Forests were used as a comparison. The Rayonier data were from 78 populations that varied in size. They were assessed with a double sampling scheme where bounded plots were the fully measured plots and a count (tally) was made on point plots to improve the estimate of basal area/ha (BA/ha). Details of population and sample sizes are given in Table 1.

TABLE 1–78 populations from the pre-harvest MARVL inventory of Rayonier NZ Ltd

	Area (ha)	Number of sample plots		
		Total	Bounded	Point
Mean	26.0	48 (1.84)*	24 (0.93) *	24 (0.91) *
Minimum	1.0	4	2	2
Maximum	94.0	177	88	89

* Figures in parentheses are number of plots per-hectare

The pilot survey in Whakarewarewa Forest had been carried out in a 27-year-old *P.radiata* stand of 1.93 ha. The following data were collected from all 478 trees in this stand: dbh estimated visually; dbh measured with a diameter tape; total height measured with a Vertex; heights of stem quality changes measured with a Vertex; visual estimates of other variables which define stem quality; and the times required to measure the above variables. The stand had a mean top dbh† of 568 mm, mean top height of 38.8 m, and stocking of 246stems/ha. Thinning and pruning had been carried out under a commonly used silvicultural regime.

† Mean top dbh is the average dbh of the 100 largest trees/ha. Mean top height is the height of the mean top dbh predicted from a height/dbh curve.

METHODS

The sample size of an inventory depends on three factors — the desired precision, the probability level, and the variation between the sampling units. Given that probability level is usually pre-specified, the desired precision and the *CV* are the critical factors determining sample size. Desired precision is expressed as Probable Limits of Error Percentage (*PLE%*, the confidence interval calculated as a percentage of the estimated mean). Variation is expressed as the coefficient of variation (*CV*) of the variable of interest. In 3P sampling, the *CV* of the ratio of measured to estimated volume (CV_R) is used. In Point-3P sampling, two *CV*s affect the precision: the *CV* of the sums of height estimates of trees in a sample point plot (CV_1), and that of the ratios of measured to estimated volume of the subsample trees (CV_2).

The ranges of CV_R, CV_1, and CV_2 in pre-harvest inventories of New Zealand *P.radiata* plantations were found through the analysis of the data. These were then used to calculate the sample size with the following functions (Shiver & Borders 1996; Wood & Schreuder 1986).

3P sampling Point-3P sampling

$$n = \left[\frac{t\,CV_R}{A}\right]^2 \qquad A = \sqrt{\frac{(t_1\,CV_1)^2}{n_1} + \frac{(t_2\,CV_2)^2}{n_2}}$$

where n = number of sample trees
n_1 *and* n_2 = number of sample points and subsample trees, respectively
t, t_1 *and* t_2 = *t*-statistic
A = allowable error (PLE%)

The average times (person-minutes) required for a unit area inventory were calculated to examine the efficiency of the various sampling methods/combinations detailed below, as explained by their variable costs. No account was taken of fixed costs. The relative proportions of the time of each operational step were also analysed to examine which had the largest effect on cost efficiency. Costs of overheads, planning the inventory, or to further analyse the data subsequent to field measurement/image processing were not taken into consideration.

The total time required (T) was calculated using the following equation. This was divided by area to give cost efficiency per unit area (Stamatellos 1995).

$$T = t_0 \sqrt{n_1 A} + t_1\,n_1 + t_2\,n_2$$

where A = inventory area corresponding to t_0 square unit
t_0 = time of walking the distance between sampling units
t_1 = time of establishing a sampling unit
t_2 = time of measuring, photographing, and image-processing of a sample tree
n_1 = number of sample units
n_2 = number of sample trees

All times are in person-minutes

Four scenarios were developed — two levels of desired precision (PLE%) × two levels of variation (CV). These scenarios were then explored using three methods:

A 3P sampling

B Point-3P sampling

C Double sampling.

For each method, the subsample trees were measured in two ways — MARVL standard field cruising procedures, and PhotoMARVL image analysis procedures.

Finally, to examine the precision of estimates of recoverable volume by log types, 3P sampling with standard MARVL was applied to the 100% measured pilot stand with a desired PLE% of 8%. The estimates of total recoverable volume and volume by log types were compared with those from 100% MARVL cruising and their standard errors were analysed.

RESULTS AND DISCUSSION

Before examining the cost efficiency of the various sampling options described in Part 2 of these results, it is necessary to determine the relationships of coefficient of variation, sample size, and PLE% for each of the three sampling options, A to C.

Part 1: Coefficient of Variation and Sample Size

A. 3P sampling

Coefficient of variation of the ratio of MARVL measured volume to estimated recoverable volume (CV_R)

Data from the pilot stand were used to calculate the probable range of CV_R. Each tree had been sampled and a visual estimate of its dbh made. Visual estimation considerably speeded up the field work by avoiding the need to walk to the tree. The estimated recoverable volumes of each tree were calculated with the visually estimated dbh and a local recoverable volume equation.

$$V = 0.0020501\, D^{1.7581} \qquad (R^2 = 0.9852)$$

where V = recoverable volume from 0.18m up to merchantable height (m^3)
D = dbh (cm, diameter outside bark at 1.4 m)

In New Zealand, a complete set of data used for constructing local volume tables with dbh and total height can also be used for developing a set of local volume tables with dbh only. The appropriate local volume equation could be read into a field computer or calculator to select the 3P sample trees. Measured recoverable volume/value was calculated from the full MARVL cruise data. The CV_R percentages obtained are shown in Table 2.

The CV_R for value varies with the relative prices of each log type so that it is difficult to generalise and use as a measured parameter. These results came from a field crew who were inexperienced in the visual measurement of dbh. With training and experience in 3P

TABLE 2–CV_R% of the ratios of measured volume and value to estimated volume.

	With malformed trees	Without malformed trees
Volume	21.1	19.7
Value*	22.0	20.7

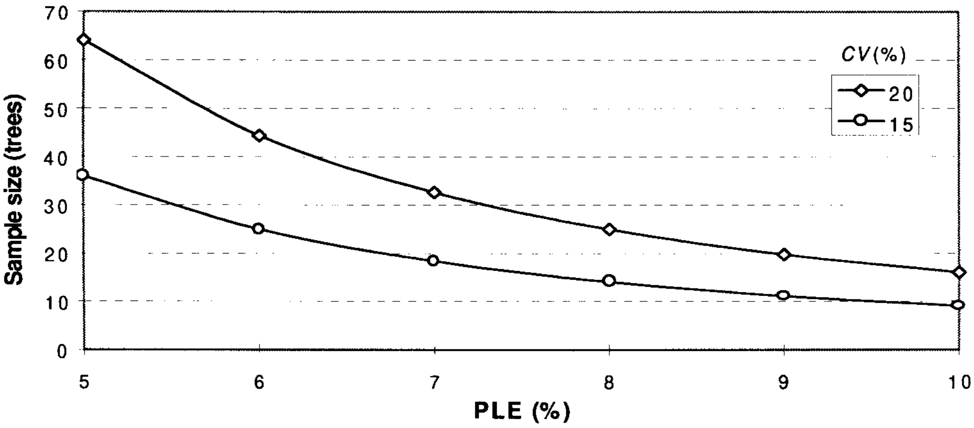
* Relative value of pruned log : sawlog : pulp log = 100 : 50 : 20

sampling, a skilled crew in New Zealand should improve their consistency and lower the CV_R to around 15%. The potential range of CV_R is therefore from 15% to 20%, and is consistent with that reported in several 3P sampling inventories carried out elsewhere (Shiver & Borders 1996; Avery & Burkhart 1994).

To determine the relationship between CV_R percentage and the variance in tree size, 15 subsets of data were generated from the 100% pilot survey so that the subsets covered a range from 2.1% to 17.2% in the *CV* of measured dbh. CV_R was calculated for each subset. CV_R ranged from 14.2% to 25.4% and showed no significant trend with the *CV* of dbh. CV_R was also examined for any trends with dbh. Values of CV_R across the dbh classes were distributed evenly around the mean value, except in the smallest dbh class, <350 mm. Iles (unpubl. data) reported that the ratio of measured to estimated volume for small trees is generally erratic. However, the proportion of trees <350 mm dbh is often small in a pre-harvest stand and so this does not critically affect the conclusion that the value of CV_R is similar across the dbh distribution.

Sample size

The subsample size of trees to be measured individually to obtain the *PLE*% for recoverable volume given *t*=2 at the 95% level of probability is shown in Fig. 1.



CV(%)	Low = 15						High = 20					
PLE(%)	5	6	7	8	9	10	5	6	7	8	9	10
n_e	36	25	18	14	11	9	64	44	33	25	20	16

FIG. 1–Potential range of sample size by recoverable volume *PLE*% in 3P sampling.

B. Point-3P sampling

Coefficient of variation of the sum of the height estimates (CV_1) in point plots

In order to calculate a value for CV_1, point sampling was simulated. The location of each tree in the pilot stand was given on a map, this was intersected with lines at 10-m intervals, and each intersection was considered as a potential point plot. Intersections within 10 m of the stand border were excluded to eliminate borderline effects; the remaining 121 intersections were simulated as point plots with varying basal area factors (BAF), and their data were analysed. The CV_1 at each point was calculated. The coefficient of variation of the number of "in" trees (and hence BA/ha) in each of the plots (CV) was also calculated to compare with CV_1 (Fig.2).

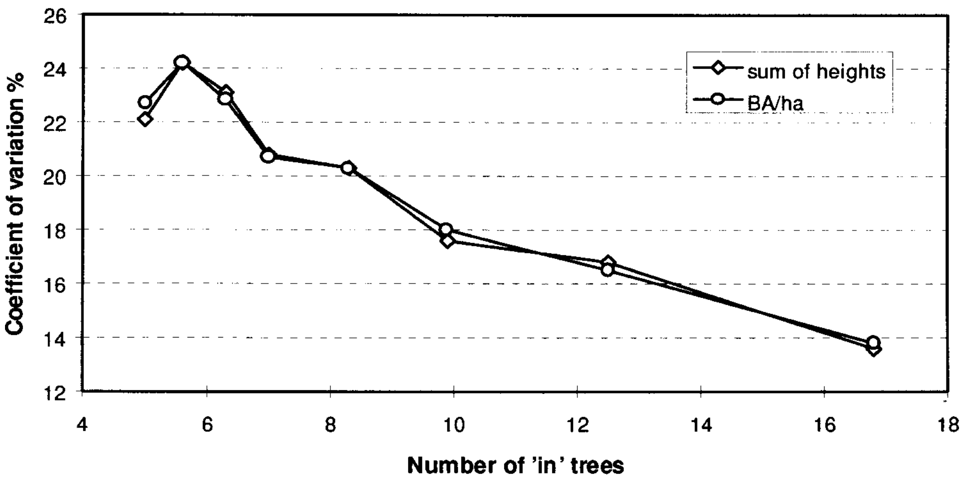


FIG. 2–Coefficient of variation of the sum of height estimates and basal area per hectare by the number of "in" trees, pilot stand

The CV was almost same as the value of CV_1, and could be used as an alternative to the CV_1 when determining sample size. The CV tends to increase as the average number of "in" trees decreases or BAF increases.

To examine the likely range of CV_1, the set of MARVL inventory data from Rayonier NZ Ltd forests was analysed. The CV of BA/ha increases with increase in the stratum area and decreases with increase in the number of "in" trees. The average values of each stratum based on point plots are shown in Table 3.

The potential range of CV% of BA/ha in New Zealand in Table 3 is from 7.5% to 58%. From these inventory data, a BAF that samples on average at least nine "in" trees at a point would be preferred to optimise efficiency. Assuming the CV_1 is equivalent to the CV of basal area as in Fig. 2, a central range of CV_1 should be from 20% to 30%.

TABLE 3–Average values of point plots in each stratum.

	BAF*	(Average number of "in" trees)	BA/ha	*CV*% of BA/ha
Mean	6.87	(7.7)	53.1	29.9
Minimum	3	(11.7)	21.2	7.5
Maximum	9	(5.2)	85.9	58.0

* BAF = basal area factor

Coefficient of variation of the ratio of MARVL measured volume to estimated recoverable volume (CV_2)

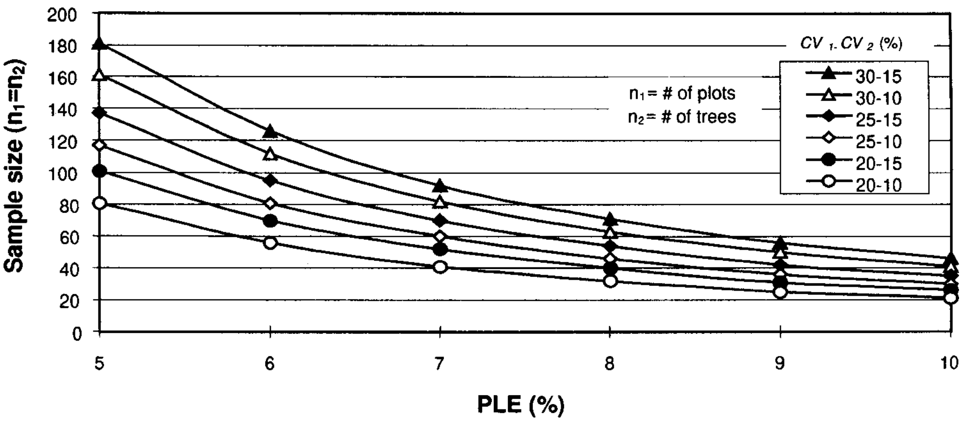
From the data of the pilot survey, the estimated recoverable volume of each tree was calculated from the local volume table as a function of visually estimated dbh. The measured recoverable volume was obtained from the full MARVL cruise measurement and the CV_2 was calculated, with (13.1%) and without malformed stems (10.7%).

Malformed trees (broken top, forks, etc.) increased CV_2, but it could be reduced to perhaps 10% through some adjustment of dbh or height of malformed trees in the field to obtain a closer recoverable volume estimate than with a volume table alone. The CV_2 could also be reduced by implementing on a field computer a recoverable volume estimation system as in MARVL where volume table, taper table, and breakage table are used along with a speedy assessment of broad-based quality features, as would occur in, for example, a mid-rotation inventory.

The potential range of CV_2 in a typical New Zealand *P. radiata* plantation would be therefore between 10% and 15%.

Sample size

The sample sizes over the potential ranges of CV_1, CV_2, and the *PLE*% of recoverable volume at the 95% level of probability are shown in Fig. 3. The desirable ratio of the number of subsample trees (n_2) to that of sample point plots (n_1) is between 1 and 2; it was assumed that n_1 was equal to n_2 in this study because a low ratio of n_1/n_2 (1) was recommended when the main variables of interest are volumes by log type (Wood & Schreuder 1986).

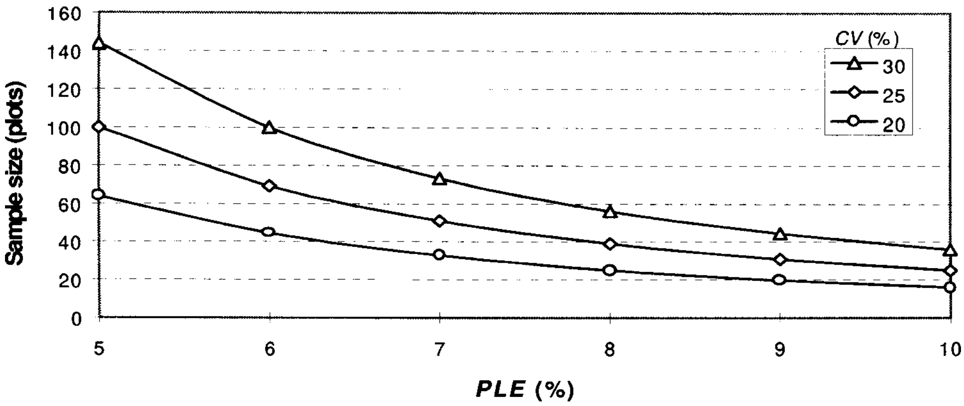


CV_1(%)		20		25		30	
CV_2(%)		10	15	10	15	10	15
	5	81	101	117	137	161	181
	6	56	70	81	95	112	126
PLE	7	41	52	60	70	82	92
(%)	8	32	40	46	54	63	71
	9	25	31	36	42	50	56
	10	21	26	30	35	41	46

FIG. 3–Potential range of sample size by *PLE*% in Point-3P sampling

C. Double sampling

There is no simple way of accurately estimating the sample size required for a given *PLE%* with double sampling (Goulding & Lawrence 1992). It depends on not only the variation of estimates in plots, but also the cost per plot in primary plots and secondary plots (Shiver & Borders 1996). In this study, the potential range of *CV* of BA/ha estimates between plots was set between 20% and 30%, the same as the CV_1 in Point-3P sampling. The total number of sample plots was calculated as though for simple random sampling over the range of *PLE%* (Fig. 4).



CV(%)	*PLE*(%)					
	5	6	7	8	9	10
20	64	44	33	25	20	16
25	100	69	51	39	31	25
30	144	100	73	56	44	36

FIG. 4–Potential range of sample size by *PLE*% in double sampling

Part 2: Cost-efficiency

In order to examine the cost-efficiency of different sampling schemes over various conditions, four scenarios were defined by two levels of desired precision for recoverable volume (*PLE*%) and two levels of between plot variation (*CV*%) (Table 4). The CV_R was fixed at 15% for 3P sampling, and 10% for Point-3P sampling. It was assumed that CV_R is independent of the variance in BA/ha of plots in Point-3P sampling and double sampling, and not determined by the variability of the population, as shown above and by Shiver & Borders (1996).

The unit times required for each measurement step, the number of personnel required in a crew in sampling procedure, and the standard stand conditions used for the analysis are shown in Table 5. Values were obtained from this study and the pilot survey, or from discussion based on the past experience of expert field crew and researchers. The BAF for point samples was assumed to vary by population to obtain eight trees per plot.

The trend of time/cost efficiency per hectare *vs* the area of a population for five sampling schema in each of the four scenarios is shown in Fig. 5. In 3P sampling a lower asymptote

TABLE 4–Scenarios of precision and variation for cost-efficiency analysis.

Scenarios	Precision* (*PLE*%)	Variation† (*CV*%)	Remarks
LP-LV	10	20	Low Precision - Low Variation
LP-HV	10	30	Low Precision - High Variation
HP-LV	5	20	High Precision - Low Variation
HP-HV	5	30	High Precision - High Variation

* Desired precision of the estimates of total recoverable volume

† *CV* of the sum of heights of plots in point-3P or BA/ha of plots in double sampling
CV of the ratio of measured to estimated volume is fixed to 15% in 3P sampling
Estimated volume is from V=f(D) where D is visually estimated dbh.
CV of the ratio of measured to estimated volume is fixed to 10% in point-3P sampling
Estimated volume is from V=f(D,H) where D is diameter-tape measured dbh and H is Vertex-measured height.

is attained for a relatively small-sized area, because all trees in a stand should be visited and their dbh predicted regardless of *PLE* and *CV*. When the 3P subsample trees are measured with a conventional MARVL field method, this asymptote is around 170 person-minutes/ha. Point-3P sampling and double sampling show low efficiency in small areas, but the efficiency improves rapidly as the area increases. Generally, 3P sampling has better cost efficiency than Point-3P sampling or double sampling in situations where high precision is desired, there is a large variation between plots, and areas are small. This is due to the difference in the sampling unit — that of 3P is a tree and the other methods include plots. Using a desired *PLE* of 10%, common in New Zealand, the marginal competitive region of 3P sampling to double sampling with conventional MARVL was between 4 and 11 ha as the between-plot *CV* increased from 20% to 30%. For stands of 4 ha or smaller, 3P sampling is the preferred option; for stands 11 ha or larger, double sampling is preferred. This marginal competitive region increased when a high precision (*PLE* within 5%) of the estimate was required, to between 20 and 40 ha. Point-3P sampling has almost the same cost-efficiency as double sampling, indicating that these two sampling methods have basically the same approach to establishing plots, outweighing other factors. The above times can be compared to the actual practice employed by Fletcher Challenge Forests. Their standard pre-harvest inventory prescription has an efficiency of around 200 person-minutes/ha on small stands and approaches an asymptote of around 70 person-minutes/ha as the area increases.

PhotoMARVL when used with 3P sampling shows higher costs per hectare than MARVL, but the difference decreases with increase in the area of the population as the additional proportion of the cost spent photographing and analysing the subsample trees in PhotoMARVL rapidly decreases as the area increases (Fig. 6). This difference increases the higher the requirement for precision. Point-3P sampling with PhotoMARVL is more costly per unit area than double sampling with conventional MARVL by around 60–70% over all conditions. PhotoMARVL is always more costly than standard MARVL under the same sampling scheme, but this differential is less when using 3P sampling. A manager's demands for high precision (5% PLE) may coincide with a demand for increased measurement detail and high accuracy. Under these circumstances, the use of 3P sampling with PhotoMARVL provides a practical method that is cost-competitive for areas less than 15 ha in size.

TABLE 5–Unit values for the cost-efficiency analysis

Procedure	Units	Values	Personnel / crew	Application methods Sampling*	Measuring†	Sources
Estimate dbh and select sample trees	minutes/tree	0.2	2	3P	M, PM	Pilot survey
Measure sample trees with MARVL	minutes/tree	3.0	2	3P, P3P	M	Pilot survey
Measure and photograph sample trees	minutes/tree	8.0	2	3P, P3P	PM	Expert field crew
Analyse image of sample trees	minutes/tree	18.0	1	3P, P3P	PM	Expert field crew
Establish point plot and select “in” trees	minutes/plot	15.0	2	P3P, DBL	M, PM	Expert field crew
Estimate heights and select sample trees	minutes/tree	0.7	2	P3P	M, PM	Pilot survey
Establish bounded plot and measure trees	minutes/plot	40.0	2	DBL	M, PM	Expert field crew
Average number of “in” trees per point plot	stems/plot	8	–	P3P	M, PM	This study
Walking speed	km/h	3	–	All	M, PM	Expert field crew
Stocking	stems/ha	250	–	All	M, PM	–

* 3P = 3P sampling, P3P = Point-3P sampling, DBL = Double sampling
† M = MARVL, PM = PhotoMARVL

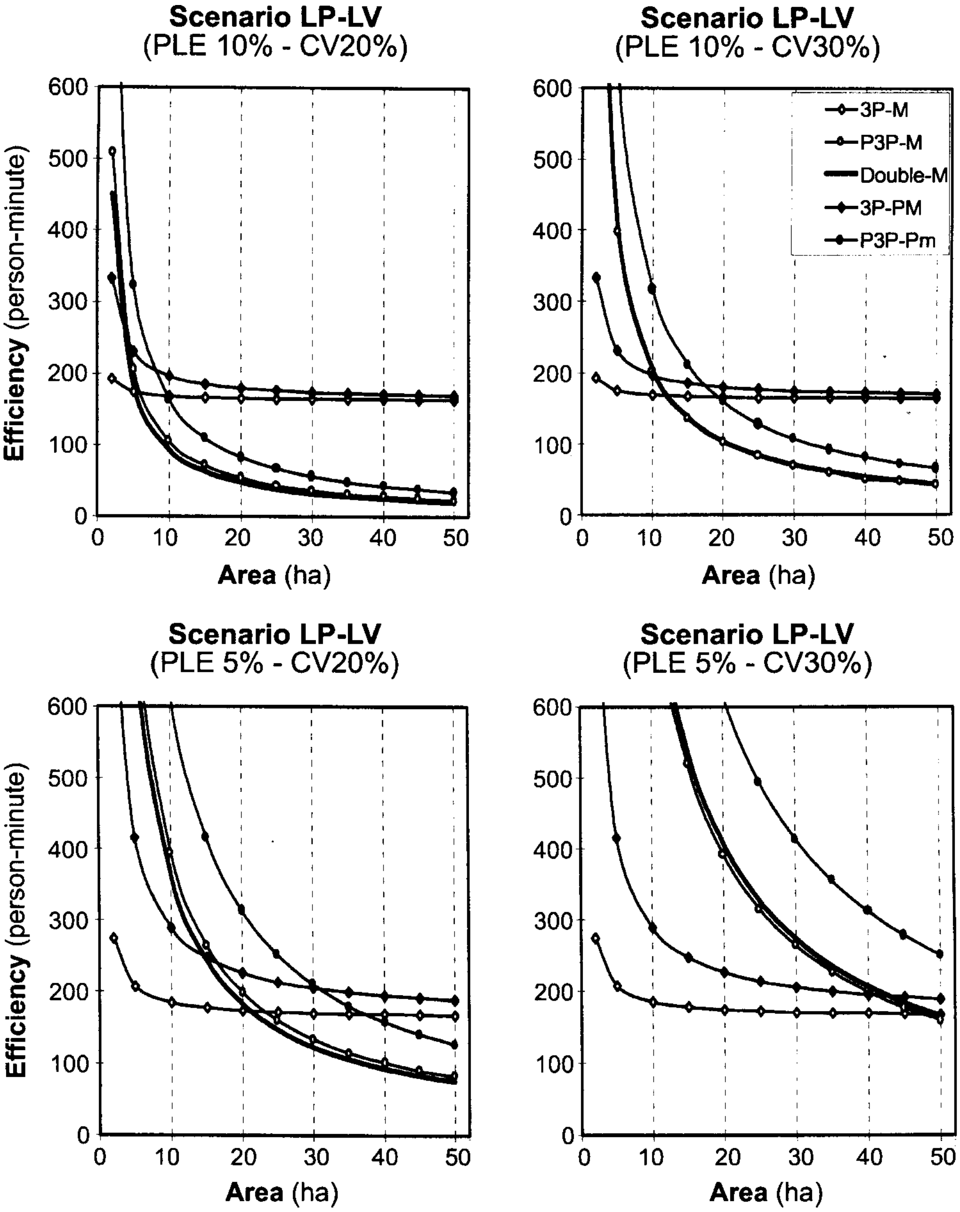


FIG. 5–Cost-efficiency of the sampling methods for each scenario

More than 70% of the total cost in 3P sampling with PhotoMARVL comes from visiting all the trees and predicting their dbh (Fig. 6). For an area larger than 15 ha, this figure goes to over 90%. In 3P sampling with conventional MARVL, the proportion of the cost of this step goes much higher. 3P sampling could extend its practical applicability to larger areas if some remote sensing and statistical techniques were available to provide an estimator well-

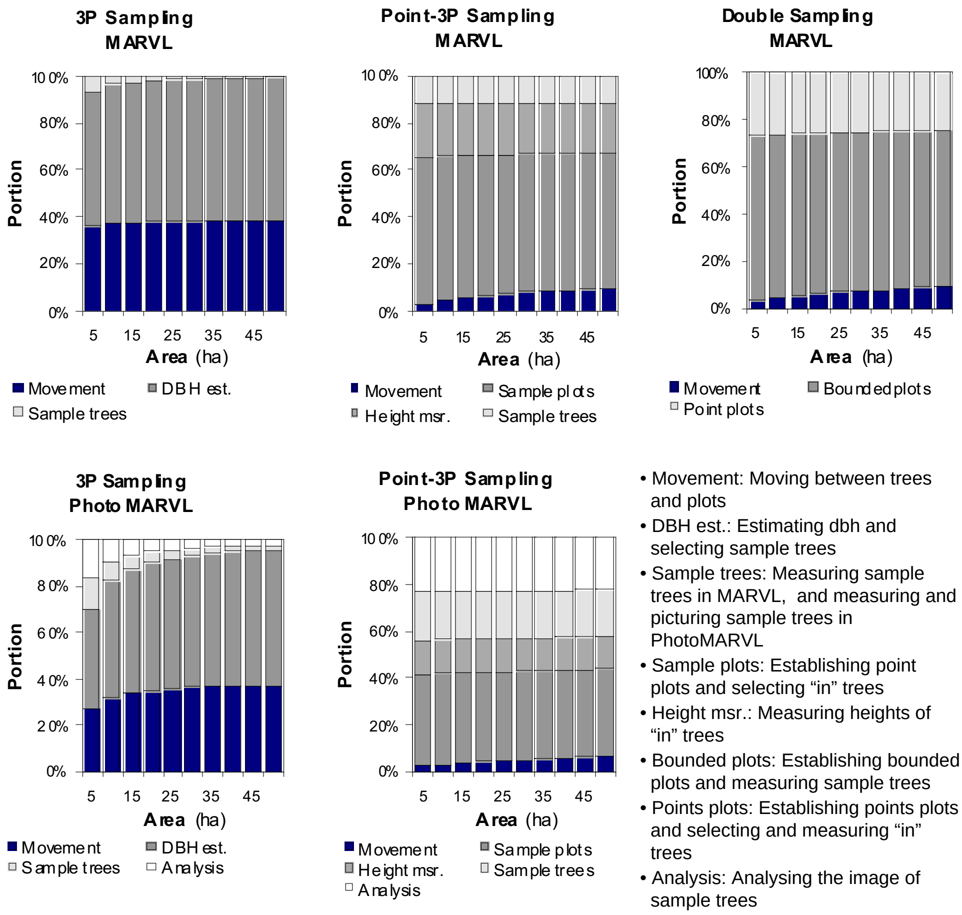


FIG. 6–The proportion of cost (person-minutes) for each of the sampling methods given that desired precision is *PLE* 10%, CV_R and CV_2 in 3P and Point-3P sampling are 15% and 10%, respectively, and *CV* of the BA/ha estimate in plots is 25%

correlated to the measured volume of tree. In Point-3P sampling and double sampling, the proportion of the cost of each step, with the exception of movement between plots, is rather constant. In Point-3P sampling with PhotoMARVL, the cost of measuring, photographing, and analysing the images of the subsample trees contributes about 40% of total cost.

Part 3: Precision of Estimates of Recoverable Volume by Log Types

3P sampling was simulated with the data from the pilot survey in Whakarewarewa Forest in order to examine the precision of the estimates of recoverable volume, subdivided into three log types: pruned logs, unpruned log, and pulpwood. The visually estimated dbh of each of the 478 trees in the stand was used to calculate an estimated recoverable volume from a local volume table, as would be possible with a field computer such as a Husky. The 3P sampling procedure selected 26 trees for detailed measurement by the standard MARVL field cruising procedure. The results are listed in Table 6.

TABLE 6–3P sampling for recoverable volumes in the pilot stand

Maximum value expected (m^3)	4.5
Sum of volume estimation in the population (m^3)	900
t-statistic at the probability level of 95%	2
CV% of the ratio of the measured to estimated volume	20
Desired *PLE* or allowable error (%)	8
Upper limit of 3P random numbers	35
Sample size (accurately measured trees)	26

The comparison between the 3P sample and 100% MARVL measurement is shown in Table 7. 3P sampling produced estimates for total recoverable volume within 2% (under-estimation) of the 100% sample, within 1% (over-estimation) by value. 3P pruned log and sawlog volume estimates were almost as good: the volume and value of pruned logs were over-estimated by 5%, sawlogs were under-estimated by 3%. Pulp log volume was under-estimated by 26%. However, the proportion of pulp logs was very small, 4.0% in volume and 1.2% in value, and would not have a significant effect on the totals. Only five of the 26 sample trees produced pulp logs.

TABLE 7–Comparison of 100% cruising and 3P sample estimates — recoverable volume and value by log types in the pilot stand

	Method		Total	Pruned	Sawlog	Pulp
Volume	A – 3P sampling	(m^3/ha)	955.6	336.3	581.2	38.1
		(%)		35.2	60.8	4.0
	B – 100% cruising	(m^3/ha)	971.7	321.4	598.5	51.8
		(%)		33.1	61.6	5.3
	A/B		0.98	1.05	0.97	0.74
Value*	A – 3P sampling		63 449	33 626	29 060	763
		(%)		53.0	45.8	1.2
	B – 100% cruising		63 098	32 138	29 923	1037
		(%)		50.9	47.4	1.6
	A/B		1.01	1.05	0.97	0.74

* Assumed relative unit value of log types as pruned log : sawlog : pulp log = 100 : 50 : 20

The precision of 3P sampling is shown in Table 8. Pruned log volumes have a lower coefficient of variation (CV_V%) of the ratio of measured pruned volume to estimated total recoverable volume than do total recoverable tree volumes. This implies that the sample size to estimate the most valuable product, pruned logs, could be reduced. Sawlogs would be estimated with a lower but still reasonable precision. However, pulp log volume had quite a large relative sampling error, as would be expected from the low proportion of trees containing pulp logs. Pulp logs, in this pilot survey, were an example of "rare" logs with only a small proportion of the trees containing this particular product. Where there is an inventory situation with very high-value "rare" logs, with large-sized individual pieces, sample size should be dictated by the variance in this log category.

TABLE 8–The precision of recoverable volume estimated for log types by 3P sampling

Statistics	Total	Pruned	Sawlog	Pulp
Mean ratio (R)*	1.065	0.375	0.648	0.042
SD_{R}	0.206	0.054	0.185	0.104
CV_{R}%	19.4	14.5	28.5	244.2
SE_{Rmean}	0.040	0.011	0.036	0.020
$CV_{Rmean} = CV_{V}$%	3.8	2.8	5.6	47.9
Volume estimates	955.6	336.3	581.2	38.1
SE_{V}	36.3	9.6	32.5	18.3

* Ratio = measured volume / estimated total recoverable volume

CONCLUSION

Individual tree sampling using the 3P sampling method is likely to be more cost-effective than plot-based sampling schemes, including double sampling with bounded and tally plots, when estimating recoverable volume for stands and woodlots which are small in area, less than about 5 ha. The higher the variation between bounded plots or point samples, and the narrower the desired confidence limits (the more precise the required estimate), the larger the area where 3P sampling is most cost-effective. This preliminary study suggests that using 3P sampling with standard MARVL field cruising could be the most cost-effective system when a low PLE of 5% is required for variable stands (a coefficient of variation between plots of 30% or more) for areas as large as 40 ha. It will also give good estimates of the volumes of log products such as pruned and unpruned sawlogs. However, it would be desirable to carry out a further study to examine the extent of any advantage of using 3P sampling with its variable probability of selection over other individual tree sampling schema with a uniform probability of selection.

3P sampling is a practical method to use when individual trees are to be measured accurately using a dendrometric method such as PhotoMARVL. A very limited number of trees need be measured by the PhotoMARVL system, except where a log product occurs only rarely within a limited proportion of the standing trees. The combination of 3P and PhotoMARVL would improve the accuracy of log product estimates by reducing any bias or uncertainty caused by the visual cruising of the standard MARVL field system. 3Psampling with PhotoMARVL would be especially applicable for smaller woodlots when the stocked area is uncertain due to irregular boundaries and when the trees are valuable enough to require more precision in the measurement of stem quality. It could extend its practical applicability to larger areas if some remote sensing and statistical techniques were to become available to provide an estimator that is well-correlated to the measured volumes of a tree and its log products. This study has made no attempt at determining the improvement in accuracy of PhotoMARVL over MARVL and it is desirable that a further study do so.

The more complex Point-3P sampling is at a disadvantage compared to conventional double sampling using standard methods of visual cruising. In larger areas, Point-3P with PhotoMARVL was found to be some 60–70% more costly than double sampling using the standard method. Further improvements to the PhotoMARVL technology are required to reduce costs.

Using 3P sampling in a standard MARVL field cruise, a woodlot with an area of 5 ha but with considerable variation in stocking or basal area per hectare could be assessed for recoverable volumes with PLE of 10% within 15 person-hours by a field crew of two. The assessment could be completed within the working day, excluding any lengthy travel time to access the woodlot. All trees would be visited, therefore it would not be necessary to know the stocked area accurately. Reducing the required PLE would not increase the amount of time required in the same way that would occur with plot-based sampling. When the area of the woodlot increased from 5 ha, the work time would increase in almost direct proportion. Incorporating PhotoMARVL to measure the subsample trees on 5 ha accurately would add a further 4 person-hours in total, including image-processing at the office. Either of these two methods would appear to be operationally viable, dependent on the value of the woodlot and the risk of financial loss due to error.

ACKNOWLEDGMENTS

The authors would like to acknowledge the considerable assistance provided by Carter Holt Harvey Ltd, Rayonier NZ Ltd, and Fletcher Challenge Forests Ltd in allowing the use of inventory data collected in their forests for the analysis used in this paper.

REFERENCES

AVERY, T.E.; BURKHART, H.E. 1994: "Forest Measurements" 4th ed. McGraw-Hill Inc., New York.

BONNER, G.M. 1972: A test of 3P sampling in forest inventories. *Forest Science 18(3)*: 198–202.

DEADMAN, M.W.; GOULDING, C.J. 1979: A method for the assessment of recoverable volume by log types. *New Zealand Journal of Forestry Science 9(2)*: 225–239.

FIRTH, J.G.; BROWNLIE, R.K.; CARSON, W.W. 2000: Accurate stem measurements key to new image-based system. *New Zealand Journal of Forestry 45(2)*: 25–29.

GOULDING, C.J.; LAWRENCE, M.E. 1992: Inventory practice for managed forests. *New Zealand Forest Research Institute, FRI Bulletin No. 171*.

GOULDING, C.J.; HOCK, B.K.; TROTTER, C.M.; HITCHCOCK, S.R. 2000: Determining the location of trees and their log products within a stand. *New Zealand Journal of Forestry 45 (1)*: 34–49.

GROSENBAUGH, L.R. 1965: Three-pee sampling theory and program "THRP" for computer generation of selection criteria. *USDA Forest Service Research Paper PSW-21*.

———1967: The gains from sample-tree selection with unequal probabilities. *Journal of Forestry 65*: 203–206.

———1971: STX 1-11-71 for dendrometry of multistage 3p samples. *USDA Forest Service FS-277*. 63 p.

———1974: STX 3-3-73: Tree content and volume estimation using various sample designs, dendrometry methods, and V-S-L conversion coefficients. *USDA Forest Service Research Paper SE-117*.

HAMMOND, D. 1995: "Forestry Handbook". 3rd edition. New Zealand Institute of Forestry (Inc.), Christchurch.

ILES, K. 1995: Point-3P sampling: extending 3P sampling to large areas. *John Bell & Associates, Inventory & Cruising Newsletter July*.

JOHNSON, F.A.; DAHMS, W.G.; HIGHTREE, P.E. 1967: A field test of 3P cruising. *Journal of Forestry 65(10)*: 722, 724–726.

MACKISACK, M.S.; WOOD, G.B. 1990: Simulating the forest and the point-sampling process as an aid in designing forest inventories. *Forest Ecology & Management 38*: 79–103.

MACLAREN, J.P. 2000: How much wood has your woodlot got? *New Zealand Forest Research Institute, Forest Research Bulletin No. 217*. 135 p.

MURPHY, G. 1998: Inventory, description, monitoring and evaluation. *New Zealand Forest Research Institute, Forest Research Directions No. 22*: 8.

SCHREUDER, H.T.; OUYANG, Z.; WILLIAMS, M. 1992: Point-Poisson, point-pps, and modified-pps sampling: efficiency and variance estimation. *Canadian Journal of Forest Research 22*: 1071–1078.

SCHREUDER, H.T.; BRINK, G.E.; SCHROEDER, D.I.; DIECKMAN, R. 1984: Model-based sampling versus point-Poisson sampling on a timber sale in the Roosevelt National Forest in Colorado. *Forest Science 30(3)*: 652–656.

SHIVER, B.D.; BORDERS, B.E. 1996: Sampling techniques for forest resource inventory. John Wiley & Sons Inc., New York.

STAMATELLOS, G.S. 1995: Comparison of point and point-3P sampling for forest volume estimation with cost analysis. *Forest Ecology & Management 74*: 75–79.

STEBER, G.D.; SPACE, J.C. 1972: New inventory system sweeping the South. *Journal of Forestry 70(2)*: 76–79.

VAN DEUSEN, P.C. 1987: 3-p sampling and design versus model-based estimates. *Canadian Journal of Forest Research 17*: 115–117.

WOOD, G.B.; SCHREUDER, H.T. 1986: Implementing point-Poisson and point-model based sampling in forest inventory. *Forest Ecology & Management 14*: 141–156.