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TESTS OF A DISTANCE TECHNIQUE FOR INVENTORY OF PINE PLANTATIONS

C. L. BATCHELER
Protection Forestry Division, Forest Research Institute, Rangiora
and
R. A. C. HODDER
New Zealand Forest Service, Christchurch

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ABSTRACT

Estimates of stocking, basal area and volume of three Canterbury pine stands were made using a distance technique and the standard New Zealand Forest Service bounded plot sampling method. Although the two techniques gave similar estimates of all three parameters, several differences in sampling characteristics were found.

The distance technique involves much less (1/28) time per sample, and about half the time to obtain estimates of equal precision, compared with the time required by plot sampling. Sample means of diameter at breast height (d.b.h.), stocking, and volume on basal area regressions all differed between the two methods, but these differences cancelled out in the determinations of average volume.

Our main conclusion is that, assuming a given amount of time and money is available for field work, the distance technique gives a more comprehensive sample of variability within a stand, and therefore that this method is less prone to errors of inadequate sampling.

1. INTRODUCTION

The experiments described in this paper arose from two considerations: interest in the possibility that a distance technique which was developed by one of us (Batcheler,

1973) for estimating stocking (density) of non-random populations could be applied to inventory of production forests and, secondly, the experience of the other (Hodder) in routine use of the standard sampling procedure (Lees, 1967) in fulfilling local management requirements in Canterbury forests.

These forests are relatively small. Different silvicultural regimes have often been employed within even a single stratum, and because of variable physiography, soils, weed competition and storm damage, variation of stocking and average tree size is often pronounced. Consequently, although sampling has been relatively intensive, covering a range of age classes, the resulting estimates have not met the specified precision (± 10% at 95% probability) required within the Service. Where estimates of individual parcels of forest have been required for local management purposes, particularly timber sales, inventory plots have commonly had to be supplemented by 20 or more additional samples.

This has placed heavy demands on staff in the forests because of the time-consuming labour involved in locating plots, marking boundaries, identifying and marking trees for height measurements, making allowances for slope, and cutting boundary lines through underscrub in hilly and weed-infested forests.

Preliminary tests of the distance method in such populations began when a series of experiments was done at Ashley and Eyrewell State Forests as part of a comprehensive study of distances for estimating non-random populations. Pine plantations were merely being used as examples of relatively uniform populations (Batcheler, 1973). However, by taking d.b.h. measurements, it was soon found that estimates of both stocking and basal area were substantially the same as had been determined from bounded plot samples.

When we realised this, it seemed worthwhile to test whether the technique could be applied to a general forest inventory. Therefore, four experiments were set up to compare estimates of stocking, basal area and volume by distance sampling with those from bounded plots.

2. METHODS OF COMPUTING ESTIMATES AND PROBABLE ERRORS

2.1 Plots

Stocking and basal area per hectare were calculated for each plot by summing the number of trees and their individual basal areas, and multiplying by 1/plot size. Volumes within each plot were calculated from the appropriate volume/basal area line as described in Section 2.3.

2.2 Distances

Full details of the method have been published elsewhere (Batcheler, 1973) so only a brief summary of points relevant to these experiments is given here.

It is well known that the estimate of stocking derived from $d = N/\pi \Sigma r_p^2$ (where d is stocking, N is the number of sample points, and Σr_p^2 is the sum of squares of N sample distances from random points to the centre of the nearest tree) is unbiased only when the population is randomly distributed. The estimate is too high if the population is uniformly distributed, and too low if it is aggregated. However, it has been found that the degree of bias of d from true density (D) can be estimated by an index of non-randomness (A) which is derived from the coefficient of variation of the point to nearest tree distances (Σr_p) and the sum of the distances from each nearest tree to its nearest neighbour (Σr_m). In the paper cited it is shown that the log of bias of d is a straight-line regression function of the index of non-randomness which takes the form

$$d/D = a.b^{-A}$$

or

$$D = d/3.473 \times 3.717^{-1.9131\sqrt{(N\Sigma r_p{}^2 - (\Sigma r_p)^2)/\Sigma r_p \Sigma r_n}}$$

in which 3.473 and 3.717 are the regression constants a and b.*

Basal area for each sample was calculated as the product of mean basal area per tree ($\bar{g}$) and D. Volumes were calculated by fitting volume basal area lines (see 2.3) to measurements of height and d.b.h. of the point and neighbour trees at each fifth sampling point, and then calculating the mean volume per tree ($\bar{v}$) by applying the volume/basal area lines to the d.b.h. measurements of all sample trees. Volumes per hectare were calculated as the product $D.\bar{v}$.

2.3 *Volume Basal Area Lines*

Using height and d.b.h. measurements of the large and small trees on the plots, or the samples at each fifth distance sample point, as appropriate, the volume of each sample tree was calculated as the dependent variable of basal area and height by log polynomial equations of the type given by Schumacher and Hall (1933), using a modified height term (J. Beekhuis, pers. comm.):—

$$\log_e v = a \log_e d + b \log_e (h^2/(h-1.4)) - c.$$

where v is volume in cubic metres, d is d.b.h. in cm, h is total height in metres, and a, b and c are constants for the particular population.

Pooled volume/basal area lines for each compartment were subsequently calculated by least squares with v (from the above formula) as the dependent variable, and basal area as the independent variable.

2.4 *Accumulating Estimates and Probable Limits of Error*

The effect of sample size on estimates of the three parameters were calculated for the plot and distance data by accumulating the samples in random order from one sample to all samples, and progressively estimating the error limits at the 95% level of probability.

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* Footnotes. 1. Example. Suppose that 100 sample points are established in a plantation and 100 point to nearest tree and nearest tree to nearest neighbouring tree distances are measured in metres. If the following are the sums of the distances and the sum of squares of the point distances,

$N = 100$, $\Sigma r_p = 163.9$, $\Sigma r_n = 227.1$, $\Sigma r_p{}^2 = 324.5$,

Then $d = 100/\pi \times 324.5 = 0.0981$ per m^2 = 981 per ha.

$$A = 1.9131\sqrt{(100 \times 324.5 - 163.9^2)/163.9 \times 227.1}$$
$$= 0.7393$$

So that $\log D = \log 981 - (\log 3.473 - 0.7393 \times \log 3.717)$
$= 2.8729$

and $D = 746$ per ha.

2. In the exponent, 1.913 is the reciprocal of the expected coefficient of variation of a sample of r_p, and is used in the formula to make A = 1 (nearly) in a sample from a random population. A is less than 1 when the population tends to be uniform, and greater than 1 when the population is aggregated.

In the example A is less than 1 and D is reduced from 981 to 746 by using the index of non-randomness.

For the plot method, estimates of the three parameters in each plot were taken as the replicates, and the probable limits of error were calculated as $t.s./\sqrt{N}$, where t is Student's t for (N − 1) degrees of freedom and S is standard deviation.

For the distance method, probable limits of error were calculated by the law of additive errors. The probable limit of error of stocking was calculated from

$$e_D = t\ A\ D\ /\ \sqrt{N}\quad \text{(Batcheler, 1975, in press)}$$

where the terms are as given in 2.2. and t is for (N − 1). Probable limits of error of mean basal area per tree ($\bar{g}$) and mean volume per tree ($\bar{v}$) were calculated by the normal distribution formula. Designating these errors as $e_{\bar{g}}$ and $e_{\bar{v}}$ the estimates of basal area per hectare (G) and volume per hectare (V) are:—

$$G = D\ \bar{g}\ (1 \pm \sqrt{(e_D/D)^2 + (e_{\bar{g}}/\bar{g})^2}\ )$$

$$V = D\ \bar{v}\ (1 \pm \sqrt{(e_D/D)^2 + (e_{\bar{v}}/\bar{v})^2}\ )$$

No account was taken of regression errors in the volume table formulae or volume/basal area lines.

3. AREAS AND EXPERIMENTS

Three areas were chosen for four experiments.

3.1 Compartment 10, Balmoral State Forest

This area is stocked by 69.2 ha of Corsican pine (*Pinus nigra* var. *laricio*) which was planted in 1932 at 2.4 × 2.4 m spacing (Fig. 1). The stand is rather patchy, with

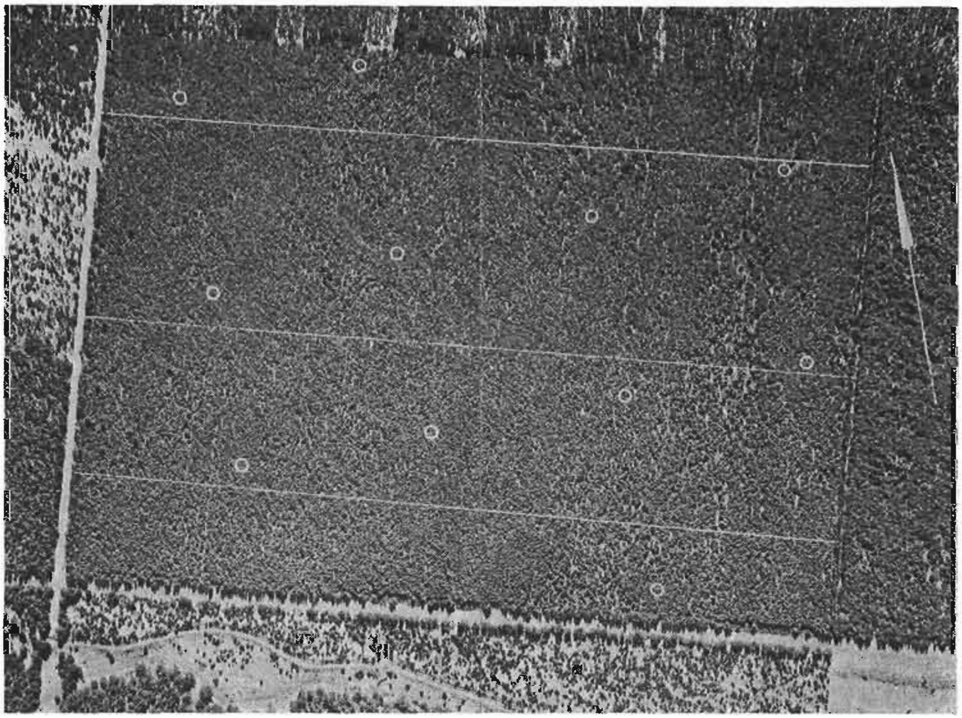

FIG. 1—Air photo. of Cpt 10, Balmoral. Bounded plot positions and distance sample lines are shown. The failure of plots to sample the poorly stocked areas is evident.

larger trees on the north side, and diffuse canopy gaps distributed in two perceptible bands across the compartment.

Eleven systematically spaced 405-m^2 plots established in 1969 according to standard procedures (Lees, 1967), were remeasured in 1973 to provide comparative figures for the distance experiment (P. Mawson, pers. comm.). Location of the sample plots is shown in Fig. 1. The d.b.h. of all trees in the plots were measured, and heights of the four largest and four smallest trees in each of three plots were estimated with a Blume Leiss clinometer.

The distance method was tested by sampling at 12.2-m intervals on three lines running from east to west. The following measurements were recorded: horizontal distance from the sample point to the centre line of the nearest tree (r_p); horizontal distance from the centre of that nearest tree to the centre of its nearest neighbour (r_n); d.b.h. of both point and neighbour trees (d_p and d_n). At each fifth point, the heights of the point and neighbour trees were estimated with a Blume Leiss clinometer (h_p and h_n).

3.2 Compartment 68, Balmoral State Forest

This stand is of naturally regenerated and thinned radiata pine (*Pinus radiata*) established after the 1955 fire (Thomson & Prior, 1958). It is relatively uniform, although there are perceptible gradients (from larger trees and complete stocking in the north-west, towards smaller trees and open glades towards the south-east), related to progressively shallower soils near the crest of an old terrace of the Hurunui River (Fig. 2). The stand had been marked for an eclectic thinning trial, and all marked trees had been counted (321 per ha, D. W. Guild, pers. comm.).

Two experiments were run in this stand to estimate stocking, basal area and volume of the total stand, and of the trees marked for retention as the crop.

Ten temporary lines were placed at restricted random intervals from origins on the southern boundary road. At 12.2-m intervals, P and n distances, p and n d.b.h. and whether or not the trees were marked for retention were recorded. In addition, p and n distances and d.b.h. were recorded to the nearest *marked* tree and its nearest *marked* neighbour. At each fifth point, heights (estimated by Abney level) of the p and n trees (marked or unmarked) were recorded. Marked and unmarked trees were tallied seperately within a 135-m^2 circular plot at each fifth point.

These data were collated to estimate the following parameters: stocking of stand and crop from sample plot counts; stocking, basal area and volume of the total stand and of the marked crop from the proportion and size of marked trees in the first sample; stocking, basal area and volume of the marked crop from p and n measurements to *marked* trees.

D. W. Guild's total count of 321 marked trees per ha ignored approximately six trees per ha which had been marked to be retained, but not pruned. Total stocking of marked trees is therefore about 327 per ha.

3.3 Compartment 2, Ashley State Forest

This is a highly variable 61.5 ha compartment of final crop radiata pine which straddles a series of ridges and gullies (Fig. 3). It was planted in 1939 at 2 m × 2 m spacing and has been thinned twice. A number of unstocked or partially stocked pockets have developed as a result of severe weed competition in the gullies and

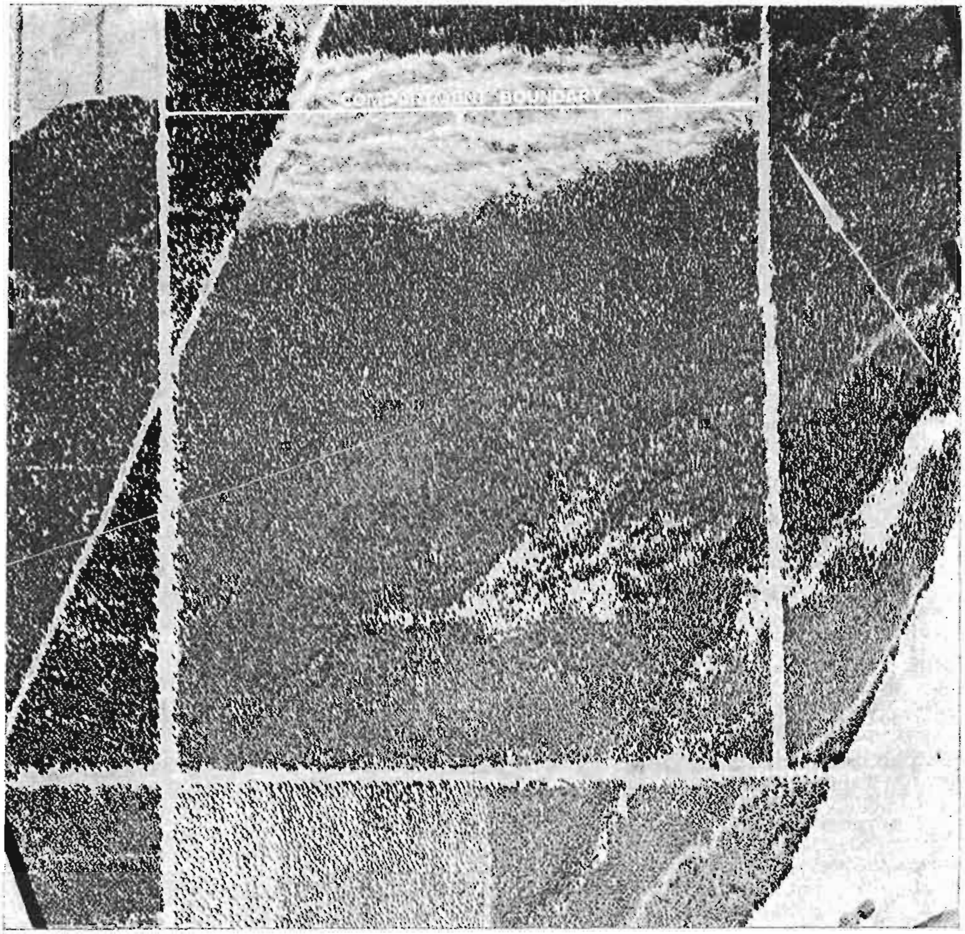

FIG. 2—Air photo. of Cpt 68, Balmoral. The area illustrates the difficulty of adequate sampling of the gradients with a small number of plots.

damage from gales on the spur flanks exposed to the north-west. These variations are compounded by a strong gradient from small trees on the ridge crests to relatively large trees in the gullies.

Twenty-six 1012-m^2 plots were established on grid lines across the compartment (Fig. 3). In each of these, all d.b.h., heights of the three trees with smallest d.b.h. and the three with largest d.b.h., and working time elapsed between leaving and returning to the compartment edge, were recorded. Seven hundred and eighty-six d.b.h. and 156 heights were measured.

Distance samples were established at 332 points spaced 12.2 m apart on the same lines. Point and n distances and d.b.h. were measured at each point and heights were measured at each fifth point. Working time on the lines was recorded. The experiment gave a sample of 664 d.b.h. and 130 heights.

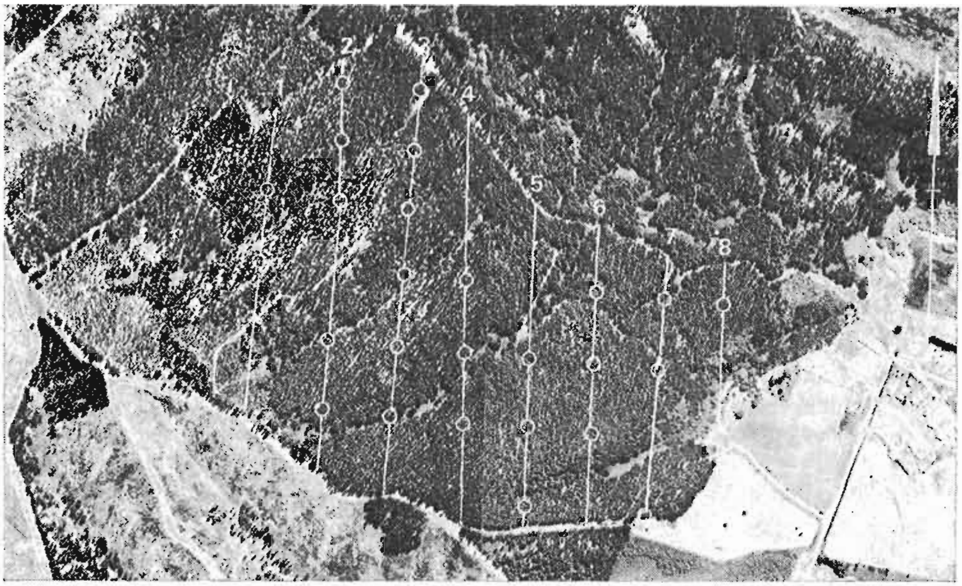

FIG. 3—Air photo. of Cpt 2, Ashley. Plot and distance sample line positions are shown as for Fig. 1. Heterogeneity of the stand is typical of Ashley Forest, and again illustrates the difficulty of adequate sampling with a small number of plots.

4. RESULTS

4.1 Overall Comparison of Plot and Distance Estimates

These experiments give figures for two comparisons of basal areas and volumes (Compartment (Cpt) 10, Balmoral and Cpt 2, Ashley) and four comparisons of estimates of stocking (Table 1). Of these, only one difference—of basal area per ha at Ashley—

TABLE 1—Estimates of stocking, basal area and volume from bounded plots and distances

	Stocking per ha mean ± 95% limits		Basal area m^2/ha mean ± 95% limits		Volume m^3/ha mean ± 95% limits	
Cpt 10, Balmoral						
Plots	993	128	62.7	9.4	332.8	46.6
Distances	895	123	59.5	8.5	354.0	51.7
Cpt 68, Balmoral						
(Stand) Plots	677	47	—	—	—	—
Distances	630	54	19.4	1.8	97.2	8.9
Cpt 68, Balmoral						
(Crop) Plots	341	30	—	—	—	—
Distances	334	29	11.3	1.0	56.8	5.2
Cpt 2 Ashley						
Plots	299	40	43.4	4.8	518.9	46.7
Distances	299	34	48.9	5.7	558.0	65.7

exceeded the PLE of the plot estimate, and could on that criterion be considered significant. Stocking estimates from the distance technique differed from the plot counts by + 1% to — 12%. In the two experiments which included basal areas, the estimates differed by — 7% and + 15%. Distance estimates of volumes were 4% and 9% larger than the corresponding plot estimates.

4.2 Comparison of Mean D.B.H.

Two comparisons are available, from the experiments at Cpt 10 Balmoral and Cpt 2 Ashley. In both cases, the mean d.b.h. per tree from plot sampling were significantly smaller than those obtained by the distance sampling ($P < 0.01$) (Fig. 4).

Part of the difference probably arises from specifications used for the two sampling methods. With the distance technique, measurements are taken whenever the sample point falls inside a line between the outermost trees of the population, provided the distance to the nearest tree is less than the distance to a permanent or clearly identifiable boundary (e.g., roadway). Standard plots, however, are required to be placed entirely within the "mapped canopy" boundary line at which stocking is judged by interpretation of aerial photographs to exceed 75 trees per ha. Consequently, there is an extremely small chance of sampling trees at the mapped canopy boundary, and no chance whatever of including relatively scattered trees. Since edge trees tend to be large, the plot sample mean d.b.h. must tend to be smaller than the average of all trees.

Difficulties of representative sampling with small numbers of plots may also have contributed to the difference. At Cpt 10, none of the plots was located in the diffuse gaps which are clearly discernible (Fig. 1).

Similarly, within Cpt 2 Ashley, there are many different "phases" of stocking, tree size and dispersion. Some of these, including smaller trees on the ridges, larger trees in the gullies, windthrow gaps on the exposed north-west faces, gaps in the gullies and low stocking along the north-east side, can be seen in Fig. 3. Other variations, such as

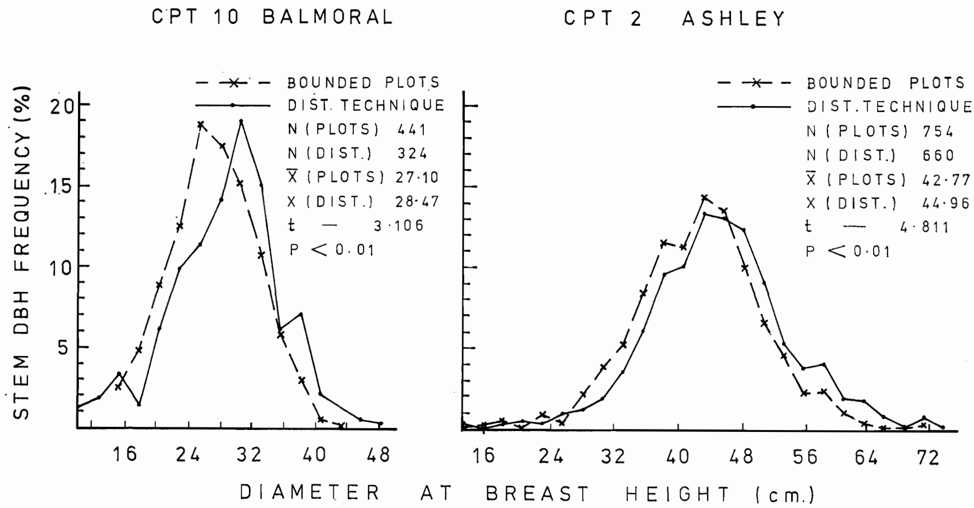

FIG. 4—Sampled d.b.h. frequency distribution for **P. nigra** (Cpt 10, Balmoral) and **P. radiata** (Cpt 2, Ashley), as given by plot and distance methods.

a set of thinning trials where current stocking ranges from approximately 1600 to 150 per ha (near the eastern end of the compartment) are difficult to see on the photo. None of the 26 plots fell in a gully bottom, in the thinning trial plots or in the wind-thrown areas of the north-west. Conversely, the distance samples included all these variations in the stand. It is therefore interesting to note that the estimates of stocking are virtually identical, but that the estimate of mean d.b.h. from the distance sample is 5% larger than from the plots ($P < 0.01$, Fig. 4).

4.3 Differences in Volume/Basal Area Lines

The five volume/basal area lines fitted to the height/d.b.h. log polynomial volume formulae are shown in Fig. 5. In all these regressions, the Y intercept constant (a) is negative, and in the two matched regressions for Cpt 10 Balmoral and Cpt 2 Ashley, the regression slopes (b) for plot samples are slightly steeper than those for the distance samples (significant at 90% level: Bml 10, $t = 1.544$, $N_1 = 64$ and $N_2 = 12$; Ashley 2, $t = 0.907$, $N_1 = 130$ and $N_2 = 156$). Cancelling these differences, however, the larger negative a constant from plot samples have the effect of giving almost identical estimates of volume of trees of mean basal area. The differences in the regression lines therefore have little consequence in estimating mean volume per tree, but it must have important effects on variance and on the distribution of tree volumes in a sample. The difference could therefore be important where the price per unit volume is related to size.

4.4 Number of Samples and Field Time Required

The effect of accumulating the plot and distance data from the first randomly selected sample, through to the Nth sample, is shown graphically for the experiments in Fig. 6, and more details of the distance experiments are given in Table 2. As shown in Fig. 6, improvements in precision of the estimates comply with the theoretical expectation of limits proportional to the square root of the number of samples. However, as these rates of reduction of errors varied for the estimates of stocking, basal area and volume, the time required for a field survey will vary according to which parameter is of interest.

At Cpt 2, for which records of field time were kept, each plot occupied a three-man crew approximately 100 minutes, and the distance work occupied a two-man crew 5.4 minutes per point. One bounded plot was therefore the time equivalent of 27.8 distance samples.

Successive computations of probable errors from 1 to N plots indicated that more than the total 26 plots established were required to estimate stocking with less than 10% probable error (Table 3). The probable requirement, from a log-log curve fitted to the data, was 28 plots. Twenty-two were required to estimate basal area and 20 were required to estimate volume. These figures are equivalent to 140 man-hours' field work to estimate stocking, 110 man-hours to estimate basal area, and 100 man-hours to estimate volume at the specified level of precision.

Field time required for the distance technique compared favourably with these figures. The probable errors of stocking, basal area and volume (calculated as given in 2.4, and summarised in Table 2) were fitted to log-log curves for progressively larger numbers of samples, and these curves were used to calculate the sample size

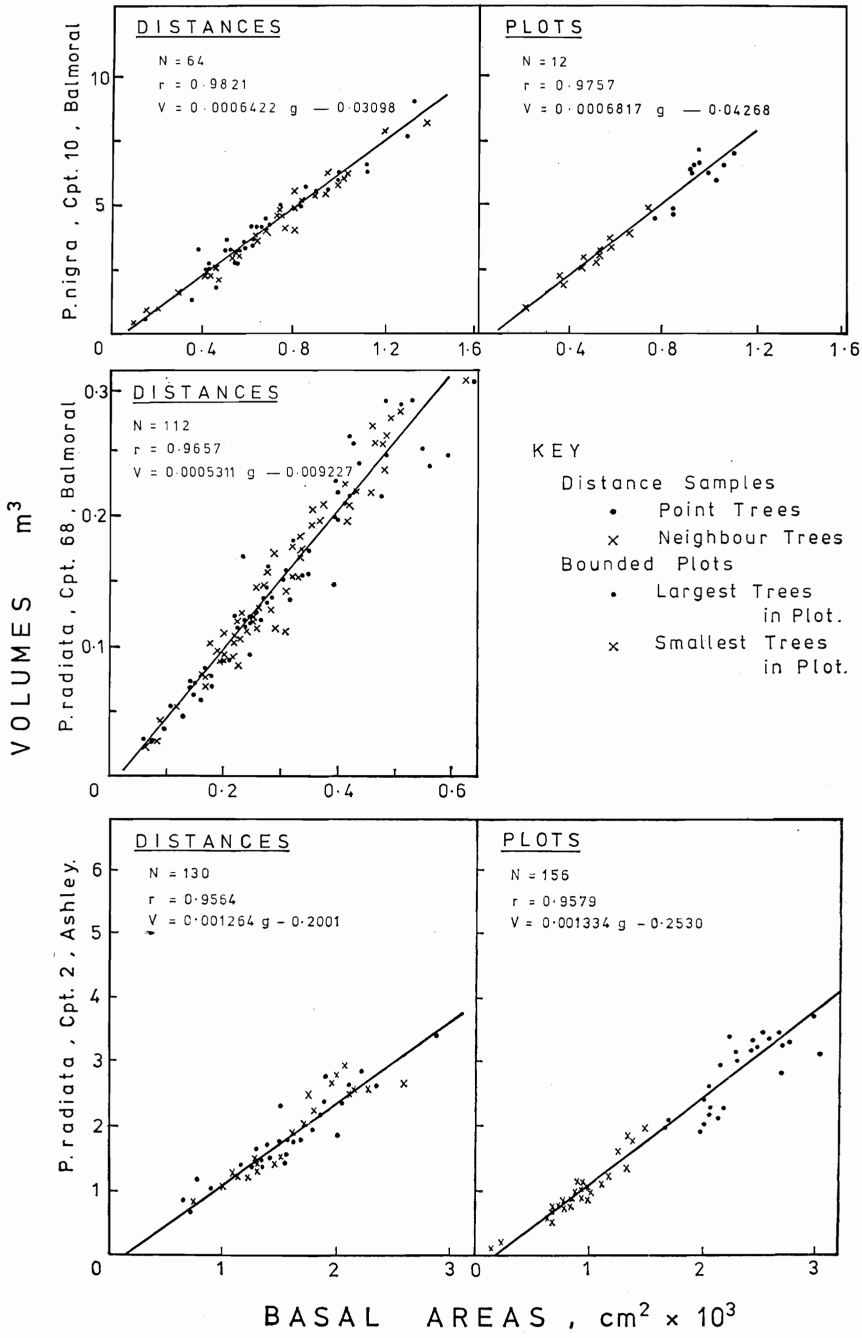

FIG. 5—Calculated volume/basal area lines and scattergrams of sample values. For clarity only one-third of the sample points are shown for Cpt 2, Ashley. Note that for distances and plots respectively, crosses refer to point trees and smallest trees, and dots refer to neighbour trees and largest trees (see Key).

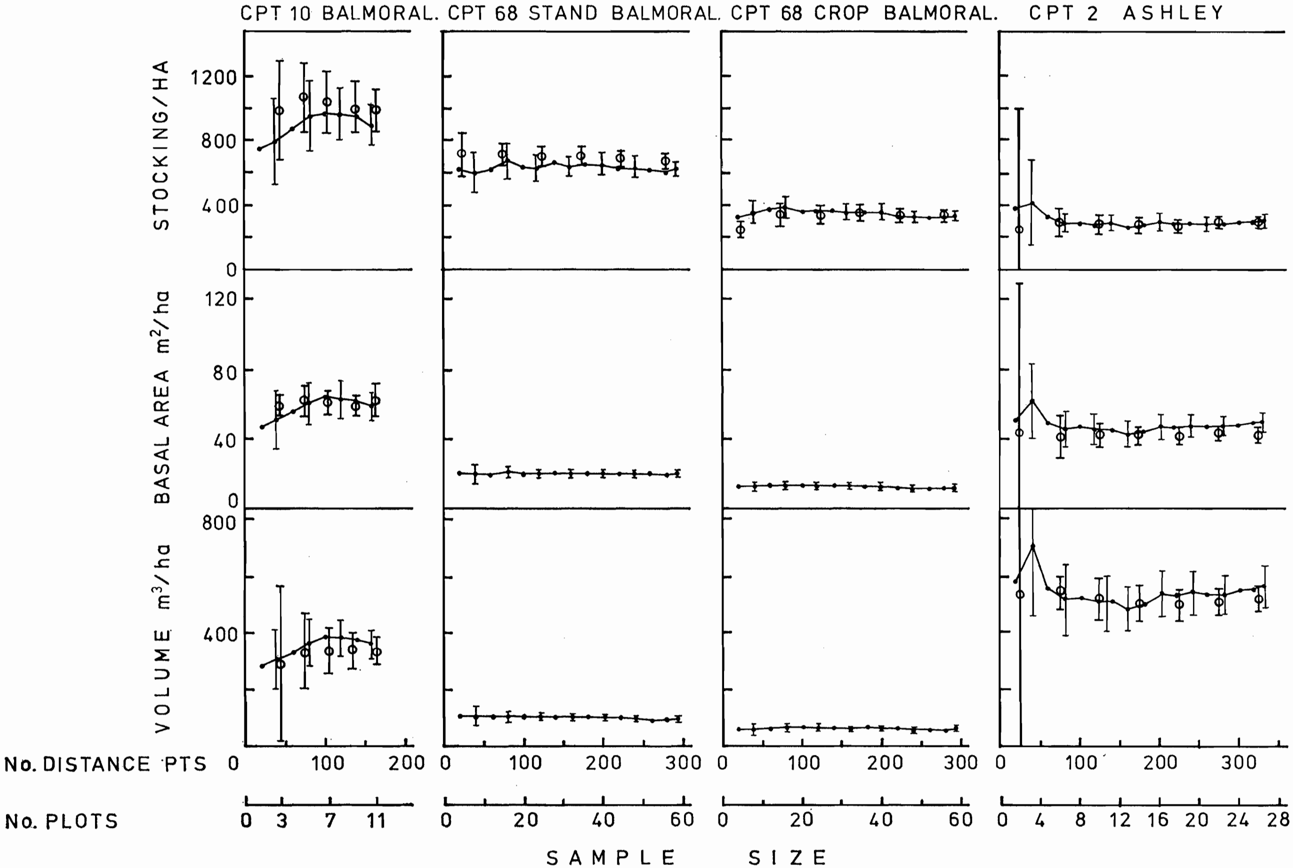

FIG. 6—Accumulated estimates of stocking, basal area and volume, for all experiments. The two scales on the abscissae are for number of distance samples (solid dots with connecting lines) and plot samples (open circles) included. The vertical bars are 95% confidence limits of the estimates.

TABLE 2 - Sampling characteristics of distance estimates associated with increasing sample size

Area	No. samples	A index	Stocking per ha D	Stocking per ha e_D%	Basal Area per tree $\bar{g}$ m² ($\times 10^{-1}$)	Basal Area per tree $e_{\bar{g}}$%	Basal Area per ha G	Basal Area per ha e_G%	Volume per tree $\bar{v}$	Volume per tree $e_{\bar{v}}$%	Volume per ha V	Volume per ha e_V%
Cpt 10,	40	1.04	811	33.1	.643	10.9	52.1	34.9	.382	11.8	309	35.2
Balmoral	80	0.97	954	21.5	.646	6.8	61.6	22.6	.384	7.4	366	22.8
	120	0.90	964	16.1	.648	5.7	62.5	17.1	.385	6.2	371	17.2
	161	0.89	895	13.7	.665	4.9	59.5	14.5	.396	5.2	354	14.6
Cpt. 68,	40	0.58	605	18.6	.326	8.7	19.7	20.6	.164	9.2	99	20.8
Balmoral	80	0.66	707	14.4	.317	5.8	22.4	15.5	.159	6.1	113	15.6
(Stand)	120	0.63	680	11.3	.309	4.9	21.0	12.3	.159	5.2	105	12.4
	160	0.66	689	9.8	.306	4.3	21.1	10.7	.153	4.6	106	10.8
	200	0.67	667	9.3	.304	3.9	20.2	10.1	.152	4.2	101	10.2
	240	0.72	638	9.1	.305	3.5	19.4	9.8	.153	3.7	97	9.8
	292	0.74	630	8.5	.308	3.2	19.4	9.1	.154	3.4	97	9.2
Cpt. 68,	40	0.62	355	19.7	.352	8.3	12.5	21.4	.178	8.7	63	21.5
Balmoral	80	0.69	385	15.2	.344	5.5	13.3	16.2	.174	5.8	67	16.3
(Crop)	120	0.80	375	14.4	.346	4.2	10.3	15.0	.175	4.5	66	15.1
	160	0.77	363	11.9	.336	3.8	12.2	12.5	.169	4.0	62	12.6
	200	0.76	348	10.5	.338	3.3	11.8	11.0	.170	3.5	59	11.1
	240	0.75	331	9.4	.338	3.0	11.2	9.9	.171	3.2	57	9.9
	292	0.75	334	8.6	.338	2.7	11.3	9.0	.170	2.9	57	9.1
Cpt. 2,	40	1.06	390	32.9	1.50	8.9	58.7	34.1	1.70	9.9	664	34.3
Ashley	80	1.04	292	22.9	1.57	6.2	45.7	23.7	1.78	7.0	519	23.8
	120	1.01	279	18.1	1.61	4.7	45.1	18.7	1.84	5.3	514	18.9
	160	0.97	267	14.9	1.60	4.0	42.8	15.4	1.83	4.4	488	15.6
	200	1.07	292	14.8	1.62	3.6	47.2	15.2	1.85	4.0	538	15.4
	240	1.07	294	13.8	1.64	3.5	48.3	14.2	1.88	3.9	552	14.3
	280	1.07	284	12.5	1.64	3.3	46.7	12.9	1.88	3.6	533	13.0
	320	1.05	292	12.0	1.65	3.0	48.0	12.4	1.88	3.4	549	12.5
	332	1.05	299	11.3	1.64	3.0	48.9	11.7	1.87	3.3	558	11.8

TABLE 3—Summary of samples necessary to estimate the parameters within ± 10% (at P = 0.95) for the four distance experiments, and requirements for both methods at Cpt 2, Ashley. N = sample numbers, MH = man-hours.

	DISTANCE METHOD					
	Stocking		Basal area		Volume	
	N	MH	N	MH	N	MH
Cpt 10, Balmoral	260		280		290	
Cpt 68, Balmoral (stand)	180		220		220	
Cpt 68, Balmoral (crop)	230		250		260	
Cpt 2, Ashley	440	79	470	85	480	87
	BOUNDED PLOTS					
Cpt 2, Ashley	28	140	22	110	20	100

necessary to obtain ± 10% precision at 95% probability. These analyses showed that, to the nearest 10 points, 180-440 samples were required to estimate stocking, 220-470 to estimate basal areas and 220-480 samples were required to estimate volume. For Cpt 2 Ashley—which was found to be the least uniform of the three populations (see A values, column 3, Table 2)—440 samples were required for stocking, 470 for basal area, and 480 were required to estimate volume. At 5.4 minutes per sample point for a two-man crew, these results are equivalent to 79 man-hours for stocking, 85 man-hours for basal area, and 87 man-hours for volume. These figures respectively represent one half, three-quarters, and nine-tenths the labour required to estimate the three parameters by the plot sampling method.

4.5 *Estimates of Compartment 68 Stand and Crop from the Two Distance Samples*

The values given in Table 1 were derived from the p, n and d.b.h. measurements to the nearest marked or unmarked trees (stand) and marked trees only (crop). This section gives further information derived from the proportion of marked trees in the stand sample.

Of the 584 trees sampled at the 292 points, 335 were marked for retention as the crop (including 8 marked to be retained but not pruned). By proportions, this gives 335/584 of 630 (Table 2) trees per ha for the crop, i.e., 361. This is 10% more than were recorded from the total count, 6% more than the estimate from the 56 plots, and 8% more than the estimate from the independent measurements to marked trees.

Unmarked trees in the sample averaged 0.137 ± 0.0042 m^3, and marked trees averaged 0.167 ± 0.0036 m^3 ($t = 5.45$, $P < 0.01$). An estimate of volume of the crop trees is therefore 361 × 0.167 m^3 per ha, = 60 m^3 per ha. This is only 3 m^3 per ha larger than the estimate based on the independent estimate of crop volume derived from measurements to marked trees (Table 2), and is within the PLE of that estimate.

5. DISCUSSION

The distance technique has been shown to yield estimates of stocking, basal area and volume which were, with only one exception, within the range of chance errors of the estimates derived from plot sampling. It therefore offers an alternative inventory technique for use in forest management.

As one of our referees pointed out, all except one of the "true values" against which the distance technique is evaluated are sample means rather than total measurements. Taken at face value, there is therefore some risk that most of the results may be quite inaccurate. The exception was obtained in Cpt 68 Balmoral where stocking of the crop trees had been determined by total count. The only possible sources of error were that some trees may have been missed, and we knew that those trees which had been marked for retention but not for pruning were not recorded (however, we also tallied these trees separately in our sampling, and obtained about 8 per ha against Mr Guild's estimate of six). The total count gave 327 per ha, our plots gave 341 $\pm$ 30 per ha, and the distance sample gave 334 $\pm$ 29 per ha. On this evidence, and the enormous literature concerned with the attributes of plot sampling, we see no reason to suspect that our results might be misleading.

Our most important conclusion is therefore that distance sampling averages are the same as obtained by plot sampling and, as shown by the records of the time worked in Cpt 2, equal precision can be obtained by distance sampling in less field time than is required for plot sampling. The essence of this comparison between the two methods is that the large number of distance samples which can be taken per unit of time gives a better chance of sampling all the variation within a stand than can possibly be encountered in bounded plots established at similar cost. This becomes particularly important where heavy underscrub hinders field work, or where a stand is extremely heterogeneous.

The results also indicate that there is considerable scope for further development of the distance technique. As shown in Table 2, mean basal area per tree and mean volume per tree were estimated within $\pm$ 10% from about 50 sample points. Consequently, the root mean square of stocking $\times$ mean basal area is predominantly influenced by the sampling errors of stocking. Many fewer d.b.h. measurements than we used would therefore suffice for measurement of basal area and volume. These results indicate that d.b.h. and height could be measured at one-quarter to one-half of the sample points, depending on the objectives. Further studies of the optimum allocation of sampling effort should take particular account of the variance of volume on basal area, but this is not feasible without better information on volume/basal area functions than exist for Canterbury plantations at present.

The advantages of simplicity and economy of the distance field procedure for sampling populations may be particularly useful in the context of management of particular forests. Within these, everyday decisions on silvicultural treatment or felling are based on estimates of stocking, basal area, volume and height of compartments or even smaller units; it follows that many advantages will accrue from a sampling system which gives estimates of all these parameters. The distance technique appears to us to satisfy these specifications because, at reasonable cost, it generates all the required estimates from a predictable number of sample trees, assuming any given number of sample points. The experiment at Cpt 68 at Balmoral also illustrated the versatility of the method for controlling thinning operations. Estimates of both the total stand and the marked crop were easily made. Recording the proportion and size of marked trees in the total stand sample gave a simple method of estimating the stocking, basal area and volume of the crop trees. Alternatively, independent sampling to the nearest marked trees and the nearest marked neighbours can be made. The first is easier; the alternative is more accurate. Regarding the Cpt 68 results, it is also interesting to notice that the indices of non-randomness of the total stand (0.74) and marked crop (0.75) are virtually identical (column 2, Table 2). Evidently the forester's selection has favoured larger trees (Sections 3.2 and 4.5) but has not improved the uniformity of distribution.

Finally, we must emphasise that the probable limits of error given throughout this paper, although comparable for the two methods, are smaller than would be computed if errors of volume/basal area functions were included. A. G. D. Whyte (pers. comm.) has drawn our attention to a recent paper which gives approximate estimates for some of the sources of errors for bounded plot sampling (Whyte, 1969). Discussion of their use and of the possibility of their extension to distance sampling is beyond the scope of this paper.

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