QUANTIFYING RESPONSES TO FERTILISER IN THE GROWTH OF RADIATA PINE

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ABSTRACT

A case is presented for using only direct estimates of volume and volume increment of a suitable sample of trees to measure responses to fertiliser in mature stands. Errors involved in estimating diameters, heights and stem volumes are briefly discussed, and methods of reducing these errors are given.

A fertiliser trial in a mature stand of radiata pine in Nelson, New Zealand, is used to demonstrate the relative success of several methods of measurement and analysis. Basal area was a poor indicator of response. Addition of a height estimate and the use of local regional volume functions gave inaccurate estimates of plot volumes and increments, as they did not take variation in tree form into account. Response to fertiliser over a 5-year period estimated in this way and adjusted by covariance analysis, had wide confidence limits (43.2 ± 42.00 m^3/ha). Sectional measurements made at the start and end of the trial, or made by stem analysis and employing general volume/d^2 regressions for the stands or treatment were also inadequate as they did not take site variation into account. A similar technique, but on an individual plot basis, yielded a more precise estimate of volume response (59.5 ± 23.34 m^3/ha) over the 5-year period. Two analyses of covariance on single trees and use of regression estimators to convert to a unit area basis gave responses of 60.8 ± 27.58 and 43.7 ± 28.73 m^3/ha. Stem analysis and statistical evaluation of single trees were also able to provide information on the responses of different tree sizes and on chosen sections within the whole stem, and for annual as well as periodic increments prior to and following any fertiliser treatment. It is concluded that stem analysis and statistical evaluation of single trees would use the benefits of analysis of covariance to best advantage.

INTRODUCTION

General volume and yield functions are not necessarily reliable methods of translating diameter and height measurements into stem volume. Reukema (1971), for example, found that the error in estimating volume growth over a 4-year period for Douglas fir subjected to stem analysis "was generally 5 to 10 percent or even greater depending on tree size and growth rate" if a 1 percent change in form factor was ignored. Whyte (1972; 1973) pointed out differences in average form within stands of radiata pine

(*Pinus radiata* D. Don), and from one rotation to the next. Woollons and Will (1975) have shown recently that form factors of radiata pine change following application of fertiliser.

This paper examines the interaction of techniques of measurement and statistical analysis, and confirms the importance of form factor.

PRINCIPLES OF MEASUREMENT

Measurements on Single Trees

Methods are reviewed in Appendix 1.

Measurements on Areal Plots or Stands

There have been suggestions that analysis of fertiliser trials should be on the basis of single-tree plots (*e.g.,* Woollons, 1974). Usually, however, forest managers require results expressed on a unit area basis, and for this reason many fertiliser experiments are laid out in plots.

Woollons and Will (1975) cite several examples where annual measurements of volume over bark are made on all trees in a plot, using a Barr and Stroud dendrometer. This represents a considerable improvement over the long-established practice of measuring only diameters at breast height and total heights, and then estimating volumes through the use of a 2-dimensional volume function. Nevertheless, the use of a dendrometer does involve a considerable amount of work without necessarily ensuring that accurate annual trends are obtained during the life of the experiment.

The technique of multi-phase sampling, usually double sampling with regression or simple regression estimators of various sorts, is a useful compromise whereby detailed and accurate annual trends of volume increment, say, can be obtained for a small sub-sample and extended to the whole experiment by means of an easy-to-measure predictor. The advantage of this approach, as in all sampling, is that greater care can be taken in measuring relatively few items, so that experimental errors are predominantly sampling errors and not a combination of these and systematic errors of measurement, which are much more difficult to isolate and account for.

The straight line relationship between volume and basal area is used here rather than a logarithmic transformation of the allometric function, $\log v = b_0 + b_1 \log g$, favoured, for example, by Miller and Cooper (1973). The figures given in their paper do not provide evidence that this logarithmic function is superior (the maximum per unit area difference was only 3.8 percent anyway). Furthermore, there are technical problems in assigning true standard errors to unit area estimates when data are transformed to and analysed as logarithms, and final results are converted back to the original figures.

METHODS AND RESULTS

Results from two treatments in a N × P factorial fertiliser trial at Braeburn, Nelson, are used to compare different measurement techniques. The experiment was established in 1968 in mature radiata pine aged 40 years which had last been thinned at age 33 (Mead, 1974). Treatments were replicated 6 times in an incomplete block design with 12 blocks. Individual plots had a net area of 810 m^2 and had treated surrounds 8.2 m wide.

Breast height bands were painted on all trees at mid-internodes (*see* Whyte, 1974) and diameter over bark to the nearest 2.5 mm measured with a tape each year from 1968 to 1973 inclusive. Trees were also numbered so that the growth of individuals could be followed. Stand height (predominant mean height as defined by Beekhuis, 1966) was measured in 1968 and derived from other measurements on the felled trees in 1973.

At the start of the trial in 1968, 20 trees from the plot surrounds were felled and sectionally measured using a 25 mm taper step (Whyte, 1971). Ten trees were selected from lower slopes and 10 trees from the ridges; within each group of 10 there were 4 large, 3 small and 3 medium-sized trees. The volumes of these trees were used to derive one of the estimates of stand volume at the start of the trial.

At the end of the trial in 1973, 5 trees in each of the 6 plots of the treatments N_0P_0 (not fertilised) and N_3P_1 + (highest levels-N, 210 kg/ha; P, 110 kg/ha; plus 8 other elements) were felled and sectionally measured at internodal points by the same taper step method as used at the start of the trial. Of these 5 trees in each plot, 3 were taken at random from the upper 20% of the diameter range and 2 from the lower 20%, excluding the lowest 5% of the diameter range.

These 60 trees were also subjected to stem analysis to provide details of annual growth trends from five years prior to the start of the trial. Tree apices between 1963 and 1973 were located and measured. Discs were cut at half breast height, breast height and thereafter at mid-internodes in taper steps of 10% of the small end diameter of the previous section down to 20 mm. The cumulative ring widths of the last 10 annual rings were measured to the nearest 0.01 mm on four equi-angular radii on each disc using an Addo-X tree ring measuring device, to which was attached a paper-tape punch. The output was processed by Program/Stem analysis (McEwen, 1975), using the full range of available checks and graphical plotting.

Gross plot volumes in 1968 and 1973 for the N_0P_0 and N_3P_1 + treatments were determined by a variety of methods.

1. A regional stand volume function, $V/G = 0.720 + 0.32\ H$ derived from local permanent sample plot data and regional 2-dimensional volume tables was used to convert plot basal area per hectare, G, and stand height, H, to volume per hectare. The data available on height in 1968 were obtained using a Blume-Leiss clinometer, whereas in 1973 they were equivalent to climbing the trees and measuring the last 5 annual increments directly.
2. A regression of volume under bark, v, on diameter at breast height over bark (d.b.h.o.b.) squared, d^2, was calculated from the sectional measurements made in 1968, $v = -0.440 + 12.1664\ d^2$, with a standard error for b_1 (s_{b_1}) of ± 4.65%, and a standard error for $\bar{v}$ ($s_{\bar{v}}$) of ± 2.8%. Two similar v/d^2 lines, each based on sectional measurements in 1973 of a random sample of 20 of the 30 felled trees per treatment were derived.

   $v = -0.546 + 12.8873\ d^2$ ($s_{b_1} = \pm 3.79\%$ and $s_{\bar{v}} = \pm 2.23\%$) for N_0P_0 and $v = -0.482 + 12.8076\ d^2$ ($s_{b_1} = \pm 2.30\%$ and $s_{\bar{v}} = \pm 1.28\%$) for N_3P_1 +

   Plot volumes were then estimated from $b_0 \times n + b_1 \times \sum_{i=1}^{n} d_i$ where n represents the number of trees in the plot and d_i the diameter at breast height over bark of the *i*th tree in the plot in either 1968 or 1973.

3. The stem analysis data from the same 40 trees used for the 1973 equations in method 2 were used to derive v/d^2 regressions in 1968 and 1973 for the N_0P_0 and N_3P_1+ treatments. The four equations were:
   $v = -0.416 + 11.9691\ d^2$ ($s_{b_1} = \pm 3.91\%$, $s_{\bar{v}} = \pm 2.22\%$) for N_0P_0 in 1968;
   $v = -0.446 + 11.9583\ d^2$ ($s_{b_1} = \pm 2.98\%$, $s_{\bar{v}} = \pm 1.60\%$) for N_0P_0 in 1973;
   $v = -0.503 + 12.2937\ d^2$ ($s_{b_1} = \pm 3.87\%$, $s_{\bar{v}} = \pm 2.25\%$) for N_3P_1+ in 1968;
   $v = -0.520 + 12.5323\ d^2$ ($s_{b_1} = \pm 2.58\%$, $s_{\bar{v}} = \pm 1.43\%$) for N_3P_1+ in 1973.
   Plot volumes for each treatment were obtained from the same formula as in method 2, using the appropriate b_0 b_1, n and d_i.
4. Volume lines were calculated for each of the twelve plots using volumes obtained from stem analysis for each year between 1963 and 1973. For all 5 years prior to 1968, the annual volumes were regressed on the square of the 1968 diameter measurements; for the years between 1968 and 1973, the volumes and diameters were matched year for year. Plot volumes were then obtained from the same formula as for methods (2) and (3).

The estimates of plot volume in 1968 and 1973 and their periodic increments obtained by these four methods are presented in Table 1. Some of the differences in the plot estimates are substantial, and this has repercussions in estimating the response to fertiliser.

Statistical Analysis of Results

Analysis of variance of a randomised block experiment carried out in the standard way showed up no statistically significant response to the fertiliser N_3P_1+, because of the wide range in site covered by each treatment and the much higher average 1968 plot volume in the N_0P_0 treatment. Plot volume increments between 1968 and 1973 were therefore subjected to analysis of covariance using straight line models. The covariate applied to the results for methods (1), (2) and (3) was plot volume in 1968; for method (4) the best covariate from the several examined was plot volume increment between 1963 and 1968. The mean responses to fertiliser in m^3/ha adjusted by analysis of covariance for methods (1), (2), (3) and (4), and their corresponding 95% confidence intervals are summarised in Table 2.

Two other methods (5 and 6) based on analyses of annual increments of single trees are included. Strictly, the data are not entirely independent within plots, as the trees were not sampled completely at random but the results can assist in indicating the relative efficiency of methods of analysis based on single trees as against aggregations of trees.

For method 5, the overall regression expressing the volume of single trees in 1973, v_2, in terms of their corresponding volumes in 1968, v_1, was:

$v_2 = -0.0559 + 1.208\ 811\ v_1$ ($s_{b_1} = 1.33\%$ and $s_{\bar{v}2} = 5.89\%$)

Differences in slopes were not statistically significant ($p > 0.05$) between the two treatment sub-classes, but those in levels were. Using the standard covariance procedures it was calculated that the mean adjusted tree volumes in 1973 for N_0P_0 and N_3P_1+ were 3.1230 and 3.3174 m^3 respectively, with S.E. of $\pm$ 0.021 19 m^3. Thus the response of an average individual tree by method 5 was 0.1944 $\pm$ 0.083 09 m^3 with 95% confidence.

In method 6, a similar regression analysis was carried out using volume increment

TABLE 1—Estimates of unadjusted plot volumes in 1968 and 1973 and their increments for treatments N_0P_0 and N_3P_1 +

Treatment	Plot	Plot Volumes (m^3/ha) in 1968, by method:				Plot Volumes (m^3/ha) in 1973, by method:				Plot Volume Increments (m^3/ha) 1968-73 by method			
		1	2	3	4	1	2	3	4	1	2	3	4
N_0P_0	7	957.3	850.5	842.1	855.6	1097.7	1005.1	964.5	962.6	140.4	154.6	122.4	107.0
	14	1104.7	924.7	915.4	956.4	1312.8	1131.9	1085.7	1133.0	203.1	207.2	170.3	176.6
	19	605.4	543.7	540.9	501.2	684.4	627.2	604.7	565.3	79.0	83.5	63.8	64.1
	21	753.2	631.0	625.7	654.4	893.1	758.9	729.3	758.0	134.9	127.9	103.6	103.6
	29	657.8	631.3	625.7	584.3	752.2	743.9	714.5	671.5	94.4	112.6	88.8	87.2
	45	756.8	654.1	651.0	639.7	851.2	744.5	726.6	718.9	94.4	90.4	75.6	79.2
	Mean	806.7	705.9	700.1	698.6	931.9	835.2	804.2	801.6	125.2	129.4	104.1	103.0
N_3P_1 +	6	745.5	701.6	685.4	736.0	920.7	890.7	856.6	923.4	175.2	189.1	171.2	187.4
	13	626.1	627.7	612.4	527.4	781.6	786.9	753.8	657.4	155.5	159.2	141.4	130.0
	15	803.2	718.4	701.8	714.6	950.1	871.3	837.1	848.8	146.9	152.9	135.3	134.2
	16	618.0	553.9	539.4	532.1	764.5	721.0	687.5	668.4	146.5	167.1	148.1	136.3
	18	852.7	778.4	760.9	766.1	1025.7	967.5	931.7	943.3	173.0	189.1	170.8	177.2
	44	877.5	744.7	727.6	780.6	1036.3	920.0	884.7	937.8	158.8	175.3	157.1	157.2
	Mean	753.8	687.4	671.2	676.1	913.1	859.6	825.2	829.8	159.3	172.1	154.0	153.7

Plot volumes estimated by following methods:

1. Stand volume equation based on 2 dimensional volume tables and estimates of basal area and predominant mean height.
2. Volume /d^2 regressions made on independent samples sectionally measured in 1968 and 1973.
3. Volume /d^2 regressions on the same 20 trees per treatment as 2 above but derived from stem analysis.
4. Volume /d^2 regressions on an individual plot basis using 5 stem-analysed trees per plot.

TABLE 2—Summary of estimated volumetric responses (m^3/ha) to fertiliser by a 40-year-old **Pinus radiata** stand

Method	1968-73 Volume increment (m^3/ha) Unfertilised, N_0P_0	Fertilised, N_3P_1 +	Response	95% C.I.
1	121.0	164.2	43.2	42.00
2	127.5	174.0	46.5	50.24
3	100.6	155.5	54.9	47.25
4	98.1	158.6	59.5	23.34
5	94.6	155.4	60.8	27.58
6	102.1	145.8	43.7	28.73

1. **See** Table 1.
2. **See** Table 1. Twenty trees sampled in 1968 and a further 20 in each treatment in 1973.
3. **See** Table 1. For 1, 2, and 3 plot volume increments were subjected to covariance analysis using plot volumes in 1968.
4. Volume /d^2 regressions on an individual plot basis (5 trees per plot) and plot volume increments between 1968 and 1973 subjected to covariance analysis using volume increments between 1963 and 1968 as the covariate.
5. Volumes on a single tree basis subjected to covariance analysis using 1968 volumes as the covariate. Volumes converted to a unit area basis using regression estimators.
6. Volume increment (1968-73) on a single tree basis subjected to analysis of covariance using individual d^2 (at breast height) in 1968 as the covariate. Volumes converted to a unit area basis using regression estimators.

of each tree between 1968 and 1973, Δv, as the dependent variable, and the square of 1968 d.b.h.o.b., d^2, as the independent variable. The overall regression was: $\Delta v = 0.175\ 61 + 2.615\ 19\ d^2$ ($s_{b_1} = 10.32\%$, $s_{\bar{\Delta v}} = 4.84\%$). In this case there was a highly significant difference in slopes of the two treatment sub-classes, and so it was necessary in adjusting treatment means to use separate regressions for the fertilised and unfertilised trees:

N_0P_0: $\Delta v = -0.1237 + 2.068\ 99\ d^2$ ($s_{b_1} = 13.85\%$)

N_3P_1 +: $\Delta v = -0.1856 + 2.996\ 76\ d^2$ ($s_{b_1} = 6.79\%$)

The mean increments between 1968 and 1973, adjusted to average d^2 over the two treatments for N_0P_0 and N_3P_1 + were 0.4215 and 0.6035 m^3 respectively. This represents a response of $0.1820 \pm 0.086\ 55\ m^3$ with 95% confidence on an individual-tree basis.

The estimates for methods 5 and 6 were converted to a ground area basis using regression estimators. For method 5 all 1973 values were adjusted for departure from the overall mean tree volume in the 12 plots as estimated for 1968 by method 4. For method 6 the mean of d^2 in 1968 was used. Volumes per hectare were obtained by multiplying by the average stocking.

With method 5, where 1973 volume is adjusted using the 1968 volume as a covariate, the volume of the N_0P_0 and N_3P_1 + treatments were 781.9 and 842.7 m^3/ha respectively, giving an estimated response of $60.8 \pm 27.58\ m^3$/ha with 95% confidence. In method 6 where volume increments are regressed on d^2, the volume increments from

1968 to 1973 were 102.1 and 145.8 m^3/ha, respectively, an estimated response of 43.7 ± 28.73 m^3/ha with 95% confidence.

Stem Form

The estimated responses to fertiliser over the 5-year period ranged from 43.2 m^3/ha or 36% of the unfertilised increment for method 1 to 60.8 m^3/ha or 64% for method 5. When gross basal area increment was subjected to similar analysis of covariance, the response to fertiliser was judged to be only 12%.

The large response in volume/ha relative to basal area/ha is indicative of a change in stem form. For the 60 trees which underwent stem analysis, Mead (1974) conducted a one-way analysis of co-variance of (under-bark at breast height) form factor in 1973, adjusted linearly with form factor in 1968. He found that there were differences from plot to plot which were associated with treatment and that this difference was very highly significant. He also showed that 35% of the total volume response occurred in the bottom two sawlogs (i.e., between 0 and 12 m), and a further 47% between 12 and 24 m. Less than 10% of the total gain was in the unmerchantable portion of the stem under 15 cm in diameter.

DISCUSSION

These results show that it is by no means easy to measure volumes or responses to fertiliser precisely on a unit area basis (Table 1 and 2). In the first three methods the 95% confidence intervals were approximately the same size as the response and even in the more precise methods they were roughly one half of the response.

Measurement of basal area does not yield a representative picture of responses as the greatest response may occur further up the stem. The response in gross basal area in the Braeburn experiment was 12% over the 5-year period; much lower than any corresponding percentage volume increase.

The addition of height as a variable and the use of regional two dimensional volume functions is not likely to improve the reliability of volume estimates (Table 1). Firstly, it still largely ignores changes in form factor; secondly, it is not an easy measurement to obtain; and thirdly, it involves too many sources of error. These errors include operator and instrument errors for diameter and height, model errors for predicting height, volume model errors and applicability of the volume model. Thus, the results are unlikely to yield an accurate estimate of volume or volume response, even if confidence limits calculated from plot volumes suggest otherwise.

Use of local volume functions collected at the beginning and end of a period has fewer measurement errors. The main errors are likely to be due to poor measurement of bark thickness and to a positive bias when diameter tapes are used. It is interesting to observe that in the Braeburn trial the 1973 volumes of the 40 sample trees based on sectional measurements were on average about 4% higher than volumes derived using stem analysis of the same trees. The volume model errors are generally low with a standard error of the mean around ± 1-2.5% when there are 20 sample trees/regression. The volume increment will therefore be measured to within about 6%. The method has the advantages of independence between volume measurements, is relatively easily performed, does not require additional height measurements with all their inherent problems and errors, and should take into account changes in tree form.

The stem analysis volumes used to construct volume/d^2 lines should provide a more accurate and more sensitive method for estimating volume increments than the method of independent samples. Any possible bias from using the same trees appears to be small (less than 4% in this example). However, both these methods were unable to detect differences in slopes or intercepts as a result of treatment although in this case the result may arise partly from the large tree size. Furthermore, the analysis of covariance of plot volume response (Table 2) produced wide confidence limits. Evidence, as yet unpublished, from other similar experiments suggests that there can be pronounced differences in v/d^2 trends on different sites, for example between trees on ridges and those on lower slopes. Thus, the fourth method of using individual regressions for each plot should overcome such problems, and lead to a more precise estimate of the response (method 4, Table 2). However, such a method tends to be much too work-intensive and even the five trees per plot used in this example were sometimes insufficient to derive reliable regressions. For example, in 1968 plots 13 and 21 had $s_{\bar{v}}$ values of 7.6 and 5.3% respectively, whereas plot 15 had a corresponding value of 1.3%.

One method of overcoming some of these difficulties would be to stratify the area according to site variation and to sample for each treatment within this. Another possibility is to use more than one covariate and possibly equations relating volume measurements to diameters at breast height and an upper stem diameter, both of which would be measured on all or a large number of trees within each plot. Tests of this latter approach are currently being undertaken.

The analysis of covariance on a single tree basis followed by a later conversion to unit area basis using regression estimators also shows promise (methods 5 and 6, Table 2). Proper use of these methods requires a consideration of experimental design beyond the scope of this paper, in that the design and sampling procedure may influence the variance to be used as experimental error.

Analysis on a single tree basis has an advantage in that it provides information on the nature of the response by different sizes of tree. It is interesting to note that the covariance analysis of volume in 1973 using the 1968 volume as a covariate did not detect a difference in regression slopes for the two treatments, thus suggesting that all trees responded the same. In contrast the slopes of the regression of volume increment between 1968 and 1973 on 1968 diameters for these same trees were highly significantly different. This result indicates that volume increment, if estimated from stem analysis, is possibly a more sensitive indicator of fertiliser response than cumulative volumes. This latter method has the further advantage of using a more independent covariate that is easy to obtain. The method could be easily applied to experimental designs with single tree plots, the results being converted to an area basis provided that the number of stems and basal area per hectare for the whole experimental population are estimated at time of establishing the experiment.

The stem analysis techniques, although tedious, have the advantages that they can readily provide annual as well as periodic estimates, growth trends prior to fertiliser application, and also direct measurements of the response by log lengths or other subdivision of the stem. Stem analysis can also be more sensitive (Table 2). Thus, regression standard errors of the mean of $\pm$ 2% could be obtained using 26 trees for methods based on sectional measurements compared with 7 for methods with stem

analysis. For large trees, as studied in this example, it would appear necessary to conduct stem analysis on 17 trees per treatment in order to obtain a standard error of the response of ± 20% of the mean.

In all these analyses reported for the Braeburn trial use of covariance completely swamped the effects of blocking. Furthermore, simple analysis of variance of a randomised block did not indicate a significant treatment response for any parameter. Analysis of covariance, therefore, is a means of obtaining more sensitive results from variable experimental material. To utilise its potential most effectively the basic measurements need to be as accurate as possible. Thus for the reasons given a sound stem analysis technique should be employed.

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APPENDIX 1 — Measurements on Single Trees

Diameter

Accurate determination of volume and volume increment depends largely on the reliability of diameter measurements and on how representative they are of radial growth along the whole stem. It is important, therefore, to adopt acceptable standards of measurement and to have a sound understanding of wood-growth patterns in the stem.

For example, although diameter over bark on a tree stem generally declines from the base upwards, this trend may be upset near branch clusters or nodes where diameters are often greater than at internodes. This is characteristic of all radiata pine in New Zealand, but is more pronounced in young than in old trees, on fertile than on infertile sites, for unpruned than for pruned stems, with uninodal than with multi-nodal branching, in the upper than in the lower parts of the stem and in open than in dense stands. Thus, if treatments or other kinds of comparisons could be confounded by the presence of side-effects such as these, care should be taken to measure diameter at points where biases are least likely to be incurred. Thus, Whyte (1974) has advocated that over-bark diameters should be taken at mid-internodes and Gleason (1972) has demonstrated that this results in the best within- and between-operator consistency of diameter measurement and the best predictive capability for less easily determined variables such as stem volume. The consequent slight underestimation of true stem volume is more than offset by greater consistency.

Choice and use of instruments to measure diameter affect the representativeness of a diameter or cross-sectional area and their respective increments. Except when the cross-section of a stem is truly circular, a diameter tape always overestimates the mean diameter, whereas direct-reading or optical calipers can produce serious positive or negative errors if only one reading is taken. Also, when more than one caliper reading is made, the geometric mean minimises errors, whereas quadratic and arithmetic means yield positive biases. Errors in estimating diameter and cross-sectional area using diameter tapes are generally small relative to two readings at right-angles with calipers (Loetsch **et al.**, 1973).

If over-bark diameter readings are repeated from time to time, it is advisable to mark the exact heights at which they were originally taken, with a band for tape readings and a cross at each tangent point for calipers. In certain circumstances dendrometer bands (e.g., Liming, 1957) or dendrographs (e.g., Fritts, 1955) could be used, but for radiata pine New Zealand rates of growth are too fast for these to work without regular readjustments. Readings to the nearest 2 mm is the best one can expect with diameter tapes, steel calipers and instruments such as the Barr and Stroud dendrometer even in skilled, reliable hands. Errors in estimating over-bark diameter growth may therefore be as high as 4 mm, which could represent a substantial proportion of annual or biennial increment.

Bark Thickness

If under-bark diameters are estimated from over-bark measurements there are further sources of error. Methods of measuring bark thickness and assumptions about the distribution of bark along and round the stem are not reliable. The common assumption that the

ratio of diameter under-bark to diameter over-bark is the same at all heights on the stem is rarely true. Bark functions, however good on average when applied to one species in a given locality, will almost invariably be subject to considerable errors for single trees; there could well be another added error if fertiliser responses influence bark thickness.

Readings taken with the commonly used Swedish bark gauge are often unsatisfactory even in skilled hands, as this instrument can be easily driven into the wood (Loetsch **et al.**, 1973). A graduated screw driver with a bluntened edge may yield better estimates on thin, unridged bark. At least four equally-spaced bark gauge readings around the circumference are needed to provide reliable estimates of under-bark diameter from over-bark measurements with a diameter tape; when two over-bark diameters at right-angles have been taken with calipers, a measurement of bark thickness should be taken at each of the four tangent points, and double bark thicknesses accorded the two corresponding diameters.

Under-bark diameters on felled stems may be measured using a bark gauge; by peeling off the bark and making direct readings with a tape or calipers; or by cutting through the stem and measuring diameter under bark with a rule across the cut face. The first two are tedious and method three may not be practicable in certain circumstances.

Height

Height is usually defined to refer strictly to the vertical distance from the tip of the tree to the ground. In measuring responses to fertiliser, however, it is more appropriate to measure the length of stem unless there is a specific requirement to determine stand height. Length of stem can be measured directly on standing trees up to about 30 m with rods or sticks (**see** Carron, 1968) and up to any height by climbing with a tape measure. The greatest source of error is in obtaining true coincidence with the tip; this can be best obtained by using either an observer up a neighbouring tree or binoculars from the ground.

Height or length of standing trees can be ascertained indirectly from the ground using a range of instruments but the errors involved in the measurement of pole crop trees or older may mark fertiliser responses. Errors may occur in using instruments by not measuring in a plane at right-angles to the lean in stem axis, inability to discern clearly the tip of the tree, making incorrect allowances for sloping distance from observer's eye to the datum and by incorrect adjustment of the instrument.

Annual height growth of pines and a few other coniferous genera can be gauged from the branching habit. Some species produce one branch cluster per year; others, such as radiata pine, may possess a multi-nodal habit, but it is still possible to identify individual winter resting points from needle scars on the stem or branch characteristics (**see** Bannister, 1962 and Jacobs, 1937). Height or height growth is not usually a sensitive enough index of total biomass responses.

Volume

One diameter together with the length of stem will not usually yield a good measure of stem volume as assumptions have to be made about the shape of the stem profile. Traditionally, the stem was divided into sections of equal length, and at least one diameter taken in each, but this method demands that measurements be made at points along the stem which may be unrepresentative because of branch swellings, defects or other such irregularities; there is also the chance that the stem profile could have a rapid drop in diameter or change in shape within one length of section. Whyte (1971, 1974) has therefore advocated that internodal diameters should be measured and that taper steps of about 10% of the previous small end diameter be used, rather than a fixed length of section. The volume of each section will be within 1% of the true mid-internodal profile volume, provided that the formula for a conical frustum is employed. The smallest diameter that need be taken and the extent of the taper step can be geared to the overall size of the tree and to specific requirements of the measurements.

Volume increment

Quantifying volumetric responses to fertiliser in a single tree involves determining volume on more than one occasion. Estimates can be obtained by climbing, or felling a

representative sample of trees, and taking sectional measurements to obtain over- and/or under-bark volume as required.

Alternatively, complete or partial stem analysis of past growth may be undertaken at the end of an experiment to derive periodic and annual increments of stem volume under bark (Whyte, 1974; McEwen, 1976). It is preferable to identify and measure the length of each annual shoot in the period under review, but one may choose to measure the diameters either in taper steps as before or at set points within annual shoots. Both methods of selecting points at which to measure diameter yield comparably accurate annual volumes and increments over a period of up to 8-10 years (McEwen, 1976), but the second method is better in this respect when longer periods are involved, and it also allows for more sensitive checks of the measurements (McEwen, 1975).

Detailed stem analysis techniques can yield very accurate estimates of volume increment under bark for each year before or during the period of an experiment. They also provide a means of estimating changes in basic density as a result of fertilisation (**see** Larson, 1973), which would be indicative of changes in strength properties or dry fibre yields. The biggest advantages are the ability to measure diameters accurately and to allow for the provision of more sensitive checks on the basic data so that more reliable estimates of volume increment can be obtained. Care is needed, however, to ensure that the mean diameter is correctly calculated depending on whether radii were measured from discs or increment cores (see Siostrzoneck, 1958).