PRODUCTION FOREST FERTILISER TRIALS: INFORMATION THEY SHOULD PROVIDE AND HOW TO GET IT

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ABSTRACT

It is essential to define the objectives of an investigation carefully at the outset, to delineate management units and biologically different populations within it, and finally to provide response information in a form that allows forest managers to forecast long-term yields. For most trials other than preliminary investigations factorial layouts of simple balanced designs are advocated, as is partial confounding in incomplete blocks or completely randomised single-tree plots. Soil and foliar analyses are considered to be useful aids for delineating populations and choosing fertiliser treatments. In turn, results from fertiliser trials can be used for refining the calibration of these diagnostic methods. Measurements taken should be appropriate to the aims of the experiment and to the variability among and within trees. Intensive measurement of a small representative sample is preferred to coarse measurement or indirect estimation of many individuals. Precautions to be taken in checking the apparent reliability of individual measurements and in adopting appropriate statistical techniques to avoid misleading results are briefly discussed.

INTRODUCTION

Forest fertiliser trials can be instigated to fulfil several functions; for example, they may be employed to detect nutrient deficiencies, calibrate foliar and soil nutrient levels, repair vegetative cover on degraded sites, screen various forms of fertiliser, develop or monitor fertiliser prescriptions (in combination with other management practices), quantify growth response surfaces, assess changes in wood quality, and so on. Because of this diversity it is important to have clearly defined objectives for any trial. Many forest fertiliser experiments over the past 25 years or so in New Zealand have been used for purposes other than those for which they were originally established, and very few have produced results from which forest managers could confidently prescribe fertiliser regimes over a wide area. This has occurred because of the difficulty in aggregating the results of several separate trials and extrapolating reliably from them.

The object of this paper is to consider what kinds of information forestry fertiliser trials should supply, and how to get reliable data as efficiently as possible. It would

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N.Z. J. For. Sci. 8(1): 178-88 (1978).

be unwise for us to generalise about fundamental research, where innovation is so important, or about the whole spectrum of forest fertilisation; attention therefore has been concentrated on applied research, that aiming to provide quantitative data which enables forest managers to predict and evaluate the potential yields from fertilised production forests.

INFORMATION REQUIRED

It is essential that any data from the results of forest fertiliser trials should be in a form that forest managers can incorporate in existing techniques for forecasting yields from their forests. However, unless forecasts show the need for more wood or the same amount from a reduced forest area, there is usually no point in investigating ways of increasing productivity through fertilisation. The wood available in New Zealand has usually far exceeded local demand, but lately this situation has been changing and there is every prospect that demand will continue to increase and ultimately outstrip supply for domestic and overseas markets. It might be quite important to ascertain, for example, whether fertilisation of young forests now could enable over-mature crops to be harvested over a shorter period to alleviate the shortfalls in wood supplies that are likely in New Zealand in the 1980s and lessen the risks associated with retaining old stands. However this sort of exercise cannot be conducted unless the benefits of fertilisation can be quantified for inclusion in yield forecasting studies.

Fertilising crops is only one of several options open to managers in order to secure the required quantities and qualities of yield from their forests. Therefore they need to know whether the monetary value of the return will exceed the compounded costs of fertiliser and its application, how this compares with other options, and also of any detrimental effects on the ecosystem. The technique of calculating present net worth in order to make financial assessments of this sort already exists, but the data needed to make the necessary evaluations are subject to considerable uncertainty. Hughes and Post (1973), in discussing this last point, stressed the lack of certainty about future prices for wood, costs of production, fertiliser costs and applicable interest rates as well as forecasting responses to fertiliser; yet all these variables are assumed to be known exactly in the traditional present net worth calculation. Nevertheless, direct financial payoffs in themselves are sometimes less important than the timeliness of increased yields, and so we focus attention on the problem of estimating responses to fertiliser. It should not be overlooked, however, that results obtained under carefully controlled research conditions may not be achieved in practice because aerial applications of fertiliser can be very uneven.

Responses to fertilisers may vary with site and from year to year as well as interact with other silvicultural operations; thus seeking an optimum treatment for each unique set of conditions is somewhat unrealistic. Middleton (1973) has stressed the importance of using an optimum based on several years' experimentation even though in certain years the recommendation will be sub-optimal. Indeed, fertiliser trials need to provide estimates of response to carefully chosen but limited ranges of fertiliser options, averaged over suitable areas and several years so that nearly optimum average prescriptions can be recommended. However an indication of the sensitivity of the response to changes in weather from year to year, in micro-site and in silvicultural practices should also be obtained The precision of the estimated response should be sufficient to assist forest managers in the confident prescription of fertiliser applications. Practical consideration of this last problem has been given by Whyte and Woollons (1977).

The variable used to assess response should be commensurable with those used in current yield forecasting techniques; usually mass of dry fibre or stem volume. However fertilisation may also produce changes in stem taper, in wood density, in number and size of branches and susceptibility to disease or other damage of the leading shoot and foliage. It is therefore necessary to quantify distribution of volume along the bole and changes in the earlywood/latewood ratios or basic density, in longevity and size of branches in certain portions of the main stem, and in amounts of malformation or defect, so that response in terms of total stem volume or total stem biomass may be qualified accordingly.

In addition it is usually advisable to try to equate these responses with assessments of foliar nutrient levels and to obtain probability estimates of the occurrence of climatically good, average and poor years for fertilisation. These data would assist forest managers to assess the likely gains in productivity through fertilising crops with known (assessed) foliar nutrient levels under a range of environmental conditions.

A comprehensive experimentation programme — one embracing a wide range of nutrients (each at several levels) over various rotation lengths, combined with or substituted for establishment, releasing, thinning and pruning operations — is obviously not feasible. Accordingly, Mead (1976) has proposed that only a very narrow range of silvicultural options should be considered and tests made on these with frequently repeated trials using several rates of a basic fertiliser regime. The regime chosen should be based on the best interpretations of growth responses, of soil and foliar analyses obtained from existing trials, on other relevant information about the site, and on present silvicultural practices and management objectives. The fertiliser regime chosen may involve application of one or more nutrients once or at several times during the rotation, and in combination with one or more other kinds of cultural practice.

Such a programme should not be implemented country-wide, but repeated in individually recognised regions such as those designated for indicative planning in New Zealand (*see* Trotman, 1973). Different land tenure, sites, species and silvicultural regimes may well exist within each of these regions, but fertiliser trials should be restricted to those strata which do or could contribute significantly to wood supplies for the whole region.

To summarise, the kinds of information forest managers require from new trials after the basic nutritional problems have been solved are:

(1) sources, rates and frequency of fertiliser application;
(2) volumetric or biomass responses which are averaged over large areas and several years, and which can be incorporated into existing yield forecasting methods;
(3) supplementary information that can be used to qualify the responses in (2) in terms of piece size and quality;
(4) corresponding assessments of foliar and soil nutrient levels for calibration purposes;
(5) records of the occurrence of good, average and poor climatic conditions for fertilisation.

This information should be available for significant and distinct populations within each regional planning unit.

EXPERIMENTAL DESIGN

Design of experiments, whatever planning framework is finally adopted, is influenced mainly by the objectives of the investigation and by the variability in the tree crops in which the experiments are to be established. If the kinds of information needed and the populations to which they should refer can be clearly established at the outset, the task of choosing a suitable and efficient design is much simplified. Practical considerations of design have been reviewed recently by Binns (1978) and Whyte and Woollons (1977), and are not re-examined here. Nevertheless, practical problems in implementing experimental designs in the field are extremely important and should be assessed as carefully as theoretical aspects.

We advocate simple balanced designs in order to avoid subsequent analytical and practical problems, of which some are mentioned later. Only two types of experiment are discussed here, namely early screening trials and ones in which stem growth responses are quantified.

Preliminary Screening Trials

When little is known about nutrient status of the soil or tree crops, forest managers may wish to:

(1) examine the nutrient status of soils about to be planted with a new species;
(2) identify nutrient deficiencies in existing stands;
(3) broadly assess responses to one or more fertilisers.

In the first category soil analysis alone is required, in the second tissue analysis together with an examination of soil properties, and in the third a simple factorial experiment. Standardised soil and foliar sampling procedures suitable for New Zealand conifer crops have been described by Mead (1974). Additional points on foliar sampling have been made by Mead and Will (1976). Because nutrient concentrations in foliage vary with age, season and position in the tree, strict adherence to the sampling procedures is essential, yet despite this nitrogen levels in particular may still be misleading. The main problem with soil analysis lies in ensuring that a sample is representative of the tree crop rooting zone. Other advantages and disadvantages of soil and tissue analysis are more thoroughly reviewed by Ballard (1977).

Both soil and foliar analysis can provide useful leads in identifying remedial fertilisers worth trying in category (3) above. A suitable design at this stage is a simple 2^n factorial as recommended by Binns (1978) for all exploratory work in tree nutrition. Mead (1974) has advocated a 2^2 factorial plus a "complete" treatment for established stands in New Zealand, to show if a response to fertiliser is possible and to determine if N and P are the limiting nutrients. The treatments he recommends are control (N_0P_0), 200 kg/ha of N (N_1P_0), 100 kg/ha of P (N_0P_1), N_1P_1, and N_1P_1 plus all other likely remedial nutrients. This kind of trial is not aimed at defining a suitable rate of fertilisation but at determining whether more detailed trials can be justified. As there is now an extensive network of such trials in New Zealand, the need for this design is lessening.

Trials to Quantify Stem Growth Responses

Fertiliser, in combination with other cultural practices, may be applied to a crop to stimulate growth at the beginning, in the middle, or at the end of a rotation. As the increase in yield at harvesting is the most crucial information a forest manager needs to decide whether or not to fertilise, experiments should last long enough to establish final yield possibilities. Traditionally, factorial experiments have proved most satisfactory for estimating growth responses to a number of cultural treatments, such as fertilisation, weeding, thinning, pruning, etc., and their interactions. However it is often impractical to test a full range of cultural treatments at a number of levels and timings in complete factorial designs. Thus compromises have to be made and there may be merit in the suggestion by Mead (1976) that factors could well be regimes consisting of a sequence of several cultural operations rather than single treatments on their own.

Were time, resources and suitable land area not critical, there would be little point in looking beyond complete factorials. All three however are limiting, and so experimenters must try to improve the efficiency of investigations. For example, a 3^3 complete factorial replicated in 4 blocks in 0.25 ha plots requires 27 ha. Finding sites that contain enough uniform areas of 6.75 ha for individual blocks is often more difficult than finding either the total area or the manpower needed.

A 3^3 factorial experiment, however, can be easily confounded with little loss of information. The single replicate design mentioned by Clutter (1968) is a particularly attractive and compact layout at an early investigational stage: it comprises 3 blocks of 9 plots thus confounding only 2 of the 8 degrees of freedom for the 3-factor (2nd order) interaction and allowing the experimenter to choose any one of the four pairs to be confounded. This layout can be repeated 2, 3 or 4 times in different years and/or other locations (within strata). With 4 replications, the partial confounding can be rotated between pairs so that, with 108 plots altogether and 70 df for the error term, the precision of estimate for all components of the 3-factor interaction is the same. When single replication only is used and the main effects are of most interest, 9 of the 12 df for the 2-factor interactions can possibly be added to the 6 df for the 3-factor interaction to form the error term, leaving only the linear component of each 2-factor interaction (*see* Yates, 1935). A 3^4 factorial can also be suitably confounded in blocks of 9 plots (*see* Cox, 1958). Details on confounding systems for other factorial designs are given by Cochran and Cox (1957).

Fractional replication of factorials with 5 or more factors is theoretically advantageous (Cochran and Cox, 1957). For example, a one-third replicate of 3^5 can be arranged in 9 blocks of 9 plots without any great loss of information on either main effects or 2-factor interactions. Binns (1978), however, considers that 5 factors in one forest fertiliser trial are too many, because of inefficiency in detecting responses and difficulty in finding areas large enough to accommodate such trials. Experience in New Zealand seems to support this contention.

The issues to be resolved in providing predictive models for estimating response surfaces are the number and magnitude of the levels used for each factor, and the form of the model. Three levels represent a minimum number to adopt, but four can sometimes be something of a luxury unless the experimenter has little or no prior information. The guessed optimum should be just lower than the middle of the range between the lowest and highest level, and the highest level should be no more than 2.5 times the guessed optimum. Finney (1972) suggests 0, 1¼ x and 2½ x for 3 levels and 0, ¾ x, 1½ x and 2¼ x for 4 levels, where x is the guessed optimum rate. Finney's simple rules for choosing the levels may be suitable for one factor, but not necessarily for more than one factor. Usually polynomials are used as models for the response, but Middleton (1973) advocates a 3 parameter exponential model for agricultural crops, and Rose (1973) has argued strongly for the adoption of biologically-based models in field experiments. We believe that while there is merit in the latter two suggestions, particularly for annual crops, much more fundamental research into forest crop models is needed before abandoning the use of simple polynomials.

In a 3^2 factorial equal weight is given to each of the 9 points which form a rectangular dispersion of levels of the 2 factors and about which the response surface is formed. Clutter (1968), because of greater efficiency through employing fewer replications, has advocated the use of central composite rotatable designs in which the guessed optimum is chosen as the centre and, unless repeated *in toto,* it alone is replicated while corner points of a rectangular grid are placed nearer the central plane than points intermediate between the corners. This design originated as a means of determining the optimum level for several factors in industrial processes where sequential experimentation was carried out and where, in certain circumstances, the response surfaces were found to be less sensitive to departures from the postulated model. Biological variation, however, is much greater than for industrial situations, because of the time scale, site variability and uncontrollable environmental factors. Thus, as the concept of a single stable optimum is not a main aim, rotatable designs may not be so advantageous in forest management trials particularly when data are incomplete. Binns (1978), concluded that these designs are more relevant to fundamental research than to management trials. The best solution for management trials may be empirical modification of Finney's simple rules.

The use of randomised blocks cannot always assist in reducing experimental error because of the difficulty in practice of finding uniform enough blocks of the required area. They may be employed advantageously in young crops or when the number of treatments per block and the size of plots are both small, But in older crops and whenever larger plots are adopted or rolling topography encountered within block variation can be too large. Woollons (1974) and Whyte and Mead (1976) quote examples for radiata pine pole and mature crops in which blocks contribute little to reducing the size of the error term. One solution offered by the latter authors is to estimate responses firstly on a per-tree basis, and convert to per unit area through use of regression estimators or multi-phase sampling.

Analysis of data from single-tree plots is satisfactory provided that plot surrounds have been adequate and suitable covariates are used, but analytical difficulties may be encountered otherwise. For example, the choice of which trees to measure in any plot, or of which plots or blocks to sample, can lead to biased estimates of the response and adoption of an inappropriate experimental error (*see* Whyte and Mead, 1976). Single-tree analysis is worth undertaking only if very careful and detailed measurements at suitable points along the stems of a representative sample can be made (*see* Whyte, 1974) and also only if the fertiliser treatments can be successfully applied in the right amounts together with a realistic portrayal of stand competition arising from the applications.

Split plots have theoretical attractions when applying fertilisers in combination with cultural treatments such as burning, clearing, seeding, cultivation, and other extensive treatments. However the number of main plots is often insufficient to provide a suitably precise estimate of the main plot treatment effects. For example, Ballard and Mead (1976) in a split-plot design reported a substantial response in the growth of young radiata pine to cultivation (the main plot treatment) but smaller responses to N and P and their interactions with cultivation were much more precisely estimated in the sub-plots. Satisfactory precision can usually be obtained for the main plot effects only with at least twelve blocks or a similar number of error degrees of freedom through repitition of a smaller design in space and time. Nevertheless, certain extensive treatments cannot easily be simulated on small areas, and split-plot designs can alleviate this problem.

For a given administrative planning unit, the design of a trial to quantify stem growth responses could proceed as follows: List strata of different species, silvicultural regimes and site types and consider only those which contribute substantial annual volume yields (say at least 10 per cent of the total annual volume yield for the whole region). Confound treatments (they may be individual nutrients, cultivation, or silvicultural practices or regimes consisting of several of these) in 3^n factorials so that main effects and any important interaction effects can be estimated with equal precision over space and time. Repeat the basic design (say blocks of 9 for a 3^3 or 3^4) in at least 3 years and try to spread the repetitions as widely over locations within strata as possible using the principle of optimal allocation among sub-strata (i.e. sample more heavily in sub-strata with larger volumes and greater variability). Locations and years could both be partially confounded with blocks, so that the whole network of individual blocks has to be analysed as a whole to provide good information. To be effective this type of approach demands simple balanced designs with enough repetition in space and time to provide adequately precise average responses for each stratum.

MEASUREMENT

Without accurate and sufficient data on the appropriate response variables, it is impossible to quantify responses to fertiliser and other silvicultural operations satisfactorily, no matter how good the experimental design. Several measures have been used in the past with varying degrees of success. The main problem is one of ensuring adequate sensitivity in the response variable subject to the time, manpower and finance available. General reviews of measuring fertiliser trials have been made by Turnbull *et al.* (1970), Mader (1973), Whyte (1974) and Binns (1978); techniques pertaining specifically to radiata pine in New Zealand have been dealt with by Mead (1974), Woollons and Will (1975) and Whyte and Mead (1976).

Although there is general recognition among the above authors that height and breast height diameter measurements alone may yield misleading estimates of volume or biomass of pole crop and older trees, some of those mentioned join other researchers in a reluctance to take additional measurements because of inhibiting costs. For example, Mader (1973) advocates:

"To get good volume-increase data at a reasonable cost, breast height increment core analysis for several trees from each diameter class is probably sufficient. Those data can be used to project diameter increase for all the trees in the stand. Sample tree height measurements can be used to construct height/diameter curves, and form-class can be determined for different diameter classes. Form-class tree volume tables or equations can then be used to compute stand volume per plot and the change in volume."

This method, although superior to many others widely adopted in practice, remains unsatisfactory because of the lack of sensitivity in the measurements taken and because of the successive functionalising of relationships without taking account of compounded model errors. Measurement of diameter increment from increment cores can be accomplished accurately, but taking cores only at breast height, where response to fertiliser may be less evident than higher up the stem, is wasting its advantage of sensitivity by sampling at the wrong position. Changes in form-class, even when the upper diameter is fixed (e.g., 6 m) rather than relative (e.g., half-height), will thus be less reliably determined than changes in inside bark diameter at breast height, but Reukema (1971), Evert (1964; 1968) and others have shown that changes in form are as important in estimating differences in increment between treatments. The successive functionalising of disregarded model errors is as follows: diameter increment is estimated from diameter, height from diameter, form-class from diameter, and volume from diameter, height and form-class. Thus the volume increment of a tree in any one year is based on three functionalised estimates not on three direct measurements. All three "independent" variables, however, are functions of diameter over bark at breast height. We contend that it is desirable to eliminate some of this successive functionalising and to try to relate response variables such as volume and volume increment or biomass directly to diameter through efficient sampling procedures (*see* Whyte and Mead, 1976).

Techniques for measuring and sampling the supplementary variables mentioned earlier, such as changes in stem volume, taper and defect in radiata pine have been described by Whyte (1974), McEwen (1976) and Whyte and Mead (1976); similarly Larson (1968) and Klem (1964) have reviewed principles and methods for assessing the wood quality of fertilised coniferous trees. All these authors stress the need to take account of morphological features of tree growth when choosing the measuring and sampling techniques to be used.

The range of measurements taken in any one trial will depend on the age of the tree crop, the objectives of the trial, and the use to which the results will be put. In very young crops height growth responses alone have often been used and are still being advocated (e.g., Binns, 1978). We consider that height growth is not always a sensitive index of response because it is strongly influenced by genotype and is less sensitive to prevailing environmental conditions (e.g., Ballard and Mead, 1976) and that it is advisable to measure diameter of the stem just above or at the root collar as well as height. For crops taller than 5 m volumes or dry weights should be accurately determined from sub-samples collected at the beginning and end of the trial; at other times measurements should be taken only when absolutely necessary such as when a trial is thinned, pruned or re-fertilised. Intermediate growth trends, if needed, can be reconstructed from stem analyses at the end of the experiment. Ancillary information such as branching characteristics, stem defects, basic density, tracheid dimensions and foliar nutrient levels can also be assessed from appropriate sub-samples. Of these only foliar samples need to be made annually as tissue nutrient levels may show large but not necessarily sustained responses to fertiliser.

Irrespective of plot size measurements for each individual tree should be recorded separately in order to improve validation of raw data, to allow single-tree covariance analysis to be used and to provide for a stock table method of yield forecasting if desired by the forest manager.

The precision needed from direct readings depends on the instrument being used, the aims of the experiment and the analytical techniques to be employed. Too often the need to check instruments repeatedly and to train operators thoroughly in taking readings is overlooked. Also, a proper consideration of rounding and calculating procedures is rarely made before deciding the precision to be adopted for single readings. As data should first be validated before being used for prediction through regression procedures, the greater the accuracy and precision of the raw data the easier it is to obtain reliable results.

ANALYSIS OF RESULTS

Raw measurements should first be subjected to the kind of checks advocated by Whyte (1969) and McEwen (1976). Chance confounding of effects may also have arisen, for example a fertility gradient or external damage imperfectly accounted for by blocking, but the resulting bias can sometimes be reduced or even eliminated by judicious choice of dummy variables in covariance analysis (*see* Yates, 1966).

Covariates in general should be chosen on biological grounds provided that they can be measured easily. Whyte and Mead (1976) considered several different covariates for adjusting volumetric responses of mature radiata pine. They concluded that a convenient measure of size such as an accessible diameter (or corresponding sectional area) taken at the beginning of the experiment sometimes suffices, but occasionally a measure of the rate of growth just prior to establishing the experiment (e.g., diameter increment over the previous few years) may also be important. If large-scale aerial photographs are taken at the time of establishing the experiment, other measures based on crown size could also be employed.

Analysis of factorial experiments is usually straightforward but complications arise when there are too many missing observations, when variances within treatments are not homogenous and in postulating the exact form of the response surface model. Unfortunately for researchers, forestry experiments are often subjected to outside interference even when careful precautions are taken. Missing observations, therefore, do occur, but orthogonality of the results can be restored at the expense of losing degrees of freedom through routines that are easily carried out on computers. This is one reason why we prefer simple rather than complex designs for forest fertiliser trials, particularly if there is some confounding of treatments. Missing data routines should also be used when validation of the data reveals suspicious items which cannot be revised by field inspection. This form of sensitivity analysis of results should not be ignored when computers are available to accomplish the necessary arithmetic easily. The assumption of approximately homogenous treatment variances is one which sometimes receives scant attention, although there are statistical computer packages (e.g., Wilson, 1976) which include such tests. In analysing fertiliser experiments where the very nature of the treatments tends to promote variation this neglect may have serious consequences, particularly when analysing widespread networks of experiments, and inferences about certain parts of the whole population could be grossly misleading. Yates and Cochran (1938) have reviewed this problem and advocate that each set of results should be judged on its merits and that modifications such as "semi-weighting" should be applied to match these individual circumstances. Finally, although polynomials usually provide adequate approximations to the form of the response surface, misleading results can eventuate if there are insufficient degrees of freedom for testing the lack of regression fit.

In reporting the final results of an experiment, mean responses and their confidence intervals for the whole and important parts of the population should be quoted in a form that can be readily assimilated in the yield forecasting method to be used for that population. If the confidence intervals do not encompass all model and sampling errors that contribute to the final results, the missing sources of error should be stated. If a manager wishes to use the lower bound in sensitivity analysis of his future yields, such under-estimates of the true confidence interval may mislead him.

CONCLUSIONS

To obtain the information needed from fertiliser trials in production forests, it is recommended that experimenters use:

(1) Simple balanced designs;
(2) soil and foliar analysis, and simple 2^2 factorials at early stages of investigation;
(3) confounded 3^n factorials repeated in at least 3 years and widely dispersed throughout the population using the principle of stratification with optimal allocation;
(4) small block sizes or completely randomised single tree plots;
(5) split plots with sufficient repetitions, when fertilisers are being studied along with cultural operations that need to be done extensively;
(6) appropriate measuring and sampling procedures which adequately detect the variation in response among and within the trees;
(7) validation of raw data and field records;
(8) analysis of covariance to allow for initial variation;
(9) polynomial response surface models.

REFERENCES

BALLARD, R. 1977: Predicting fertiliser requirements of production forests. **In** Use of fertilisers in New Zealand forests. **N.Z. For. Serv., For. Res. Inst., Sympos. 19:** 33-44.

BALLARD, R. and MEAD, D. J. 1976: Uniform fertiliser-site preparation trials in the Auckland Conservancy. Results after 2 years (A578, A580, A581). **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 73** (unpubl.).

BINNS, W. O. 1978: A guide to practical fertiliser experiments in forestry. IUFRO (in press).

CLUTTER, J. L. 1968: Design and analysis of forest fertilisation experiments. Pp. 281-8 **in** "Forest fertilisation — theory and practice". TVA, Muscle Shoals, Alabama.

COCHRAN, W. G. and COX, G. M. 1957: "Experimental designs". 2nd ed. John Wiley & Sons Inc., New York.

COX, D. R. 1958: "Planning of Experiments". John Wiley & Sons Inc., New York.

EVERT, F. 1964: Components of stand volume and its increment. **J. For. 62(11):** 810-13.

——— 1968: Form height and volume per square foot of basal area. **J. For. 66(4):** 358-9.

FINNEY, D. J. 1972: "An introduction to statistical science in agriculture". Blackwell Scientific Publications, 4th ed.

HUGHES, J. M. and POST, B. W. 1973: Economic considerations in forest fertilisation. **In** Forest Fertilisation Sympos. Proc., **USDA For. Serv., Gen. Tech. Rep. NE-3:** 45-54.

KLEM, G. S. 1964: The effect of fertilisation on three quality properties of Norway spruce. **Norsk Skogbr. 10:** 491-4 (**Transl. UK For. Comm. No. 235, 1965**).

LARSON, P. R. 1968: Assessing wood quality of fertilised coniferous trees. Pp. 275-80 **In** "Forest Fertilisation — theory and practice". TVA, Muscle Shoals, Alabama.

MADER, D. L. 1973: Fertiliser needs and treatment responses for wood fibre production: field assessment. **In** Forest Fertilisation Sympos. Proc., **USDA For. Serv., Gen. Tech. Rep. NE-3:** 140-54.

McEWEN, A. D. 1976: An examination of the accuracy of the data collected from yield research plots of the Forest Research Institute. Ph.D. Thesis, University of Canterbury, 452p.

MEAD, D. J. 1974: Standardised methods for forest fertiliser trials. **N.Z. For. Serv., For. Res. Inst., Soils and Site Productivity Rep. 50** (unpubl.).

——— 1976: Design of fertiliser trials for management. Paper to division 1, XVI IUFRO Congress, Oslo.

MEAD, D. J. and WILL, G. M. 1976: Seasonal and between tree variation in the nutrient levels in **Pinus radiata** foliage. **N.Z. J. For. Sci. 6(1):** 3-13.

MIDDLETON, K. R. 1973: Design and analysis of superphosphate trials on high-producing permanent pasture. **N.Z. J. Agric. Res. 16:** 497-502.

REUKEMA, D. L. 1971: Consideration and problems in determining volume growth of individual trees. IUFRO Section 25, XV Congress, Florida.

ROSE, C. W. 1973: The role of modelling and field experiments in understanding complex systems. **Proc. Sympos. Armidale Sept. 1973:** chap. 10, pp. 129-54.

TROTMAN, I. E. 1973: New procedures in forest management planning in the New Zealand Forest Service. **N.Z. J. For. 18(1):** 81-6.

TURNBULL, K. J., GESSEL, S. P. and STOATE, T. N. 1970: Growth response analysis for fertiliser experiments. Pp. 119-26 **in** "Tree Growth and Forest Soils." Oregon State Univ. Press, Corvallis.

WHYTE, A. G. D. 1969: Some computer programs for Elliott 503 to handle stem analysis and tree growth. **N.Z. For. Serv., For. Res. Inst., Mensuration Rep. 15** (unpubl.).

——— 1974: Measuring responses to fertiliser in growth of radiata pine. Pp. 141-56 **in** "Fertilising Forests", ed. A. Edmonds, Univ. of Waikato, Hamilton, N.Z.

WHYTE, A. G. D. and MEAD, D. J. 1976: Quantifying responses to fertiliser in the growth of radiata pine. **N.Z. J. For. Sci. 6(3):** 431-42.

WHYTE, A. G. D. and WOOLLONS, R. C. 1977: Design, measurement and analysis of forest fertiliser experiments in New Zealand. **In** Use of fertilisers in New Zealand forests. **N.Z. For. Serv., For. Res. Inst., Sympos. 19:** 45-58.

WILSON, J. B. 1976: **Teddy Bear Satistical Program. Tech. Rep. T5** (2nd ed.) Otago Univ. Computer Centre.

WOOLLONS, R. C. 1974: Forest fertilisation experiments on Taupo pumice — some notes on experimental design, analysis and planning. Pp. 137-40 **in** "Fertilising Forests", ed. A. Edmonds, Univ. of Waikato, Hamilton, N.Z.

WOOLLONS, R. C. and WILL, G. M. 1975: Increasing growth in high production radiata pine stands by nitrogen fertiliser. **N.Z. J. For. 20(2):** 243-53.

YATES, F. 1935: Complex experiments. Supplement to **J. Roy. Stat. Soc. II(2):** 181-247.

——— 1966: A fresh look at the basic principles of the design and analysis of experiments. **Proc. 5th Berkeley Sympos. on Mathematical Statistics and Probability Vol. IV:** 77-90.

YATES, F. and COCHRAN, W. G. 1938: The analysis of groups of experiments. **J. Agric. Sci. 28(4):** 556-80.