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BY

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SUMMARY

Growth data obtained from sixty continuous forest inventory plots on an irregular eucalypt forest in New South Wales have been used to develop multiple regression equations for the prediction of the following types of stand growth:—

1. Basal area growth excluding ingrowth.
2. Basal area ingrowth.
3. Basal area growth including ingrowth.
4. Volume growth excluding ingrowth.
5. Volume growth including ingrowth.
6. Useful volume growth including ingrowth.

The predictive models for basal area growth and volume growth were composed of three significant variables, one of which was a measure of stand density or age, the second a measure of stand composition, and the third a measure of site quality. These three variables are generally considered to exhibit a strong degree of mutual independence; this fact lends considerable support to the legitimacy of the technique.

The equations were used to predict the mean growth rates for the forest during the growth period following that from which the equations were developed, and the predicted values were compared with those actually observed. The predicted values for individual plots were also compared with the actual values. The testing of the regression models against an independent set of data is rare in this type of investigation, but is necessary for a critical evaluation of the technique.

It was found that the mean basal area growth excluding ingrowth was predicted almost exactly, but that basal area ingrowth was predicted poorly, so that the mean basal area growth including ingrowth was underestimated by 17 per cent. The mean volume growth excluding ingrowth was underestimated by 10 per cent, and when ingrowth was included, by 12 per cent. Useful volume growth was underestimated by 18 per cent.

Some possible reasons for the differences have been advanced and from these some suggestions have been made about variables which might be incorporated into future models. Most of these require the future accumulation of other data from the plots.

The order of accuracy of the prediction of volume growth per acre was found to be comparable with that obtained by a standard stand-table projection method using CFI growth data, and considerably better than a stand-table projection using growth data obtained from sources other than CFI data.

The proposed predictive model method is considered preferable to the stand-table projection method because it is based on a dynamic approach to stand growth, because it provides considerable additional information, and because it does not require data on the growth of individual trees.

It is claimed then that the technique described here can be used to construct, for the growth of irregular stands, mathematical models which are not only consistent with the past growth of the stands on which they are based, but can also be used to predict the future growth of the stands with an accuracy which has been shown empirically to be quite reasonable.

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AN INVESTIGATION INTO THE GROWTH OF IRREGULAR EUCALYPT STANDS IN NEW SOUTH WALES

INTRODUCTION

One of the most frustrating problems which confronts the forester in the task of providing forests for the future is the great difficulty of predicting the future growth of his forests with any degree of precision.

In most long-term enterprises the prediction of future demand is the question which occupies the greatest attention of management planners; future supply can be geared to this predicted demand by the manipulation of controllable variables. In forestry enterprises there is a similar difficulty in predicting future demand, but the manipulation of the variables is restricted, in that one of them, the climate, is not controllable, another, the soil, is difficult and expensive to control, and a third, the biotic environment, is so complex that the precise effect of altering it is not easy to predict. Unless the growth rate is known, the amount of growing stock necessary to meet future contingencies cannot be accurately assessed.

Australia is at present planning on a national scale to alleviate a future shortage of timber by a major expansion of the softwood plantations programme. Until these plantations begin to contribute significantly to the timber requirements of the country, there will be increasing demand on the native eucalypt forests, and there is an urgent need for accurate growth information on these forests so that detailed plans to cover the interim period can be formulated. Since Canada and the United States are exporters of timber to Australia, it would not be expected that the problem has the same urgency in those countries; yet a survey recently conducted there amongst forest mensurationists revealed that the general question of growth and yield is the problem occupying the greatest amount of attention in this field (Homer and Sayn-Wittgenstein, 1963).

The sustained yield principle that the allowable annual cut on a forest should equal its annual increment has always prompted much of the thought and research on the prediction of forest growth. All of the many formulae and methods which have been devised for calculating allowable cut require some estimate of rate of growth, whether it be in the form of rotation length, increment percent, or mean or current annual increment.

The only way that these growth rates can be estimated is on the basis of experience; i.e., the observation of past growth rates. Obviously, this is easiest on the basis of individual trees. Trees which have prominent annual growth rings can be subjected to stem analysis and their dimensions at any point in the past can be determined. Trees which lack this feature can be periodically measured over a period of time and their history similarly plotted.

A great deal of effort has gone into analyses of the causes of the wide variability in growth rates of individual trees. These analyses are difficult enough when even-aged forests are being considered, but the problem is immensely complicated in mixed, irregular forests. In the latter case it must have seemed to the European foresters of the late 19th century that the only possible way of discovering the growth rate of the forest as a whole was to measure every tree on it. And in fact in several small selection forests this was actually done, the technique forming the basis of the check method of forest management (Biolley, 1920; Schaeffer, Gazin and d'Alverny, 1930).

In countries where the ratio of foresters to trees made it highly impractical to measure every tree periodically, the theory of sampling was invoked to reduce the magnitude of the task of measurement to a practical level. Even so it was found that in order to obtain an acceptable sampling error, the number of trees required in the sample still created a formidable analytical task. The transfer of the tedious part of the analysis to punched card machines and later to electronic computers was responsible for a revolution in this method of obtaining growth information, and for the development of the continuous forest inventory (CFI) system.

There is a voluminous literature on the advantages, disadvantages, and techniques of CFI in North America where it was originally formulated. Osborne (1949) gave a brief outline of the advantages and disadvantages of the system, Meteer (1953) discussed the need for growth data in forest management, and Wright (1954) outlined the type of information a large paper company expected to get from CFI. The proceedings of two symposia which touched on most aspects of CFI have been published (University of Georgia, 1959; Purdue University, 1960). Cutler (1955) described its value in ponderosa pine stands, and Baker and Hunt (1960) discussed its use on a small property. Stott and Semmens (1960) enthusiastically expounded the philosophy of continuity of control by continuity of inventory. The statistical advantages of permanent sample plots in reducing the sampling error of growth estimates have been formulated by Hall (1959), Bickford (1954, 1960, 1962) and Bickford, Mayer and Ware (1962). Tagudar (1960) described plans for establishing CFI in the Philippines, and Forrest (1961) outlined the general pattern in New South Wales. Shain (1963) more recently reviewed the status of CFI in the United States and Canada.

While there are differences of opinion about certain aspects of CFI technique, such as the size, shape, and type of plots, degree and method of field marking, and so on, the basic philosophy of the CFI system has widespread accord. The following concepts are common to almost all CFI systems:—

1. The basic purpose of CFI is to obtain information about growth. Any other information obtained is ancillary.
2. The sampling unit is the plot, the arrangement of these being systematic or random.
3. It is essential that the plots receive the same treatment as the rest of the forest, i.e., that they not be favoured in any way.

4. Due to the high correlation between successive measurements, a high degree of precision in growth estimates can be obtained with a relatively small number of plots, i.e., many less than would be necessary for an estimate of standing volume to the same precision.

5. Because of the large amount of data collected and the advantages of getting growth information that is up-to-date, it is highly desirable that some form of automatic data processing be used.

There seems to be somewhat less accord (and, incidentally, literature) about what to do with the growth information obtained through CFI, and doubts have been expressed as to the efficiency of CFI for obtaining the type of growth information desired by management (Grosenbaugh, 1959; Davis, 1959 and 1964). It is apparent that the early enthusiastic advocacy of CFI created the impression of an all-embracing managerial panacea, and some reaction was inevitable.

Experience in Australia has shown that there is at least one forest situation where there is no substitute for some form of CFI if forest growth information is required. The eucalypts, which constitute the bulk of the natural forests of Australia, do not produce defined annual rings, with the exception of a few species of the south-eastern highlands. This precludes any type of stem-analysis method for obtaining growth data. At the same time most of the commercial forests have suffered from a long period of selective cutting which has created irregular forests with components of indeterminate age. Under these conditions, the practice of applying growth data obtained from isolated research plots to the whole forest, as has been necessary in the past, has proved to be of questionable merit, since these plots have received specialised treatment and thus cannot be considered of the same population as the rest of the forest. CFI has proved to be the only way of obtaining reliable growth data applicable to the whole forest.

It is not intended here to negate the value of research plots or to suggest that CFI plots can substitute for them. CFI information may be used to assist the selection of factors to be used in designed experiments, but essentially, CFI plots and research plots have quite different objectives. The purpose of research plots should be to indicate the path that managerial practices need to follow to increase the productivity of the forest, whereas the analysis of CFI data will indicate to what degree the forest is responding to these applied research findings, and, by short-term projection, will be used to predict its future response.

The method which is used to carry out this short-term projection depends to some extent on the nature of the data collected. Almost all CFI systems provide at least enough information to draw up a detailed stand-table and, with this, diameter increments by size classes can be estimated by some such technique as the (double rising)/(double effective) method of Schaeffer, Gazin and d'Alverny (1930), or the Prodan method. Stand-table projection can then be used as if the diameter increments were obtained by stem analysis (Wahlenberg, 1941; Meyer, 1942). If the trees are individually identified, then the actual average growth rates by size classes can be obtained, preferably using automatic data processing to do so, and stand-table projection is again applicable.

The principal alternative to some form of stand-table projection for prediction of growth rates of irregular stands is a method which correlates stand growth with stand characteristics and predicts through this relationship. The theoretical advantage of this type of technique is that the number of assumptions necessary is reduced, although some of the more sophisticated approaches to stand-table projection are more than comparable with the simpler stand equation methods in this respect. For instance, in the basic stand-table projection method, the assumptions are made that the average diameter growth and volume per tree of a certain diameter class are constant. In the predictive equations method, mathematical models of the growth of the stand are created using elements which have a strong correlation with stand growth, such that virtually the only assumption made is that factors which have had a strong relationship with growth in the past will have a similar strong relationship with it in the future. The method is only as good as this assumption is true.

For some years now, growth information from permanent plots has been used to derive predictive multiple regression equations. Workers in the pre-computer age were severely restricted by the impracticability of testing more than a few variables, but valuable contributions were made by Simmons and Schnur (1937), Duerr and Gevorkiantz (1938), Herrick (1944), Buell (1945), Spurr (1952), Deetlefs (1954), and Warrack (1959). The new era was ushered in by the development of computer programmes for multiple regression analysis, one of the most useful being that of Grosenbaugh (1958). Since then, considerable work has been done on the growth of the southern pines, e.g., Bennett, McGee and Clutter (1959), Clutter (1963), Nelson *et al.* (1961 and 1963), and Nelson (1964). Buckman (1962) carried out a very interesting study on red pine, Mesavage (1961) worked on shortleaf pine, and Lemmon and Schumacher (1962) did an analysis of ponderosa pine growth. Similar studies are under way in Europe; for instance, that of Kuusela and Kilkki (1963) on Scotch pine in Finland.

It will be noted that all the recent literature cited concerns various species of pine, usually occurring in pure, even-aged stands. In almost all cases the significant variables have been found to be combinations and transformations of age, site, and stand density. The question which is raised in this paper is the suitability of the same technique for deriving predictive models for the growth of stands containing many species of indeterminate age, as exemplified by an irregular eucalypt forest in New South Wales, Australia.

There have been very few published accounts in which comparisons have been made between the growth rates as predicted by either the stand-table projection method or the stand model method, and the growth rates actually observed during the period of prediction. Such comparisons must have been made; the paucity of literature may indicate the lack of spectacular success in the field. Without such comparisons, odious though they may be, there is no way of deciding the relative merits of different methods of prediction, nor of finding out the weak links in individual methods.

The aims of this study, then, are to investigate a technique for predicting the growth of irregular forests and to test its validity empirically. The technique has the following characteristics:—

1. The data on which the predictions are based are the results of two successive measurements of CFI plots on a forest.
2. Predictions are in terms of basal area and volume growth of stands, or, more specifically, of plots, in stands rather than of the average diameter growth of individual trees.
3. Multiple regression analysis is used to derive predictive equations which have measurable stand characteristics as independent variables. The choice of variables will depend on their biological rationality as well as on their statistical significance.
4. Automatic data processing is used wherever it is applicable.

The predictive equations are used to predict the growth of the forest from the time of the second measurement, and these figures are compared with the actual growth rates. From these comparisons, conclusions regarding the value of the prediction technique are drawn. A comparison is also made between the volume growth per acre as predicted by this method, the volume growth as predicted by a simple stand-table projection, and the observed volume growth per acre.

HISTORY OF CFI ON COOPERNOOK STATE FOREST

Coopernook State Forest[1], which is part of Manning River National Forest, is an area of about 2,200 acres of high quality eucalypt forest administered by the Forestry Commission of New South Wales. It is situated about 250 miles north of Sydney, about ten miles from the Pacific Ocean.

Topographically, the area is undulating to flat; slopes of over five degrees are rare. Elevations range from sea level to 1,000 feet. The forest has a sub-tropical climate with a 55-inch rainfall fairly well distributed throughout the year but with a summer peak and often a spring drought. Recorded temperatures range from 25 to 114 degrees Fahrenheit, but monthly mean maxima range from 62 to 82 degrees, and monthly mean minima from 49 to 68 degrees.

Most of the soils are derived from shales of Triassic or more recent age. These have produced clay loams which vary to some extent in colour, depth and gravel content. In general, the best soils for tree growth are the dark red, deep soils of the gentler topography; poorer growth occurs on the yellow-grey, gravelly, shallow soils of the steeper ridges and on the grey waterlogged soils where drainage is impeded.

In common with other sclerophyll forests of Australia, the vegetation is dominated by the genus Eucalyptus. Of the major commercial species occurring on Coopernook State Forest, only 2 per cent by volume are not eucalypts. As in most of the eucalypt forests of the coasts of northern New South Wales and southern Queensland, the major species of this forest is blackbutt (*Eucalyptus pilularis* Sm.)[2], comprising about 80 per cent of the total volume, and distributed fairly uniformly over the whole area. There is a discontinuous understorey of forest oak (*Casuarina*), and the shrub layer "is typically sparse, consisting mainly of *Casuarina* and *Acacia*, whilst the forest floor is typically dominated by Bladey Grass (*Imperata*) and Bracken (*Pteridium*)" (Curtin, 1962).

The dominance of blackbutt on this area has been a significant factor in its history. The species is highly prized by foresters, sawmillers and consumers. It is one of the fastest growing of the eucalypts under favourable conditions, growing straight, tall, and free of low branches. The average blackbutt on Coopernook in eighty years can reach a diameter breast height (d.b.h.) of 28 inches, a merchantable height of 60 feet and a total height of 120 feet.

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[1] The history up to 1954 and geography of Coopernook State Forest are described in more detail in the Manning River National Forest Management Plan, written for the Forestry Commission of New South Wales by R. A. Curtin.

[2] The ecology of blackbutt was the subject of an extensive study by Florence (1961).

The wood is pale brown, uniformly textured, usually straight-grained, and of moderate density with good strength characteristics, making the timber suitable for a wide variety of purposes. Blackbutt timber from Coopernook State Forest is used for fruit cases, for most requirements of building construction, including framing, weatherboards and flooring, and in heavy construction.

Much of the forest as it is now has resulted from regeneration following heavy cutting of the stands between 1872 and 1892, and again between 1915 and 1918, so that now very little evidence of the virgin stand can be found. In 1918 the forest came under working plan control; the group-selection system of silviculture was instituted and intensive treatment followed. From 1929 to 1942, the forest was used by the Australian Forestry School for working plan exercises, and management control was intensified. Between 1942 and 1954 the annual cut was fixed, logging became systematic, and further treatment and thinnings were performed. From 1950 a deliberate policy of encouraging blackbutt regeneration came into force. This was achieved by enlarging the canopy openings created by logging so that the less-tolerant species would be favoured.

In 1954 a 10 per cent strip-line assessment was followed by the formulation of a management plan, which recommended a reduction in the allowable cut, with most of the felling to be concentrated in the large size classes in order to build up the deficient medium size classes. After some initial problems the plan was successfully implemented.

Because of its long history of management and its high growth potential, Coopernook State Forest was selected as the site for a study of the feasibility of using continuous forest inventory in native hardwood forests in New South Wales. In January 1957, sixty half-acre, rectangular permanent plots were installed on a grid system, giving a 1·4 per cent sample, by Forester R. A. Curtin and three students, one of whom was the author. All trees over 4 inches d.b.h. in the plots were well marked and their positions, sizes and descriptive details individually recorded. Descriptive features of the plot as a whole were also noted. Details of the field procedure are given in Appendix 1.

The plots were remeasured in January 1960, in order to assess the value of the CFI system. The analysis of this growth period has been very well documented by Curtin (1962). His findings significantly influenced the design of CFI systems on other state forests, and determined the type of computer analysis required, as well as having a marked effect on the management of Coopernook State Forest. The principal effect with respect to the latter was the decision to retain as growing stock a significant proportion of the largest vigorous trees, which had been shown to have a much greater increment than previously thought, and to compensate for them by cutting less vigorous trees in the next smaller size class. An indication of the fruitfulness of this policy has been demonstrated in the results from the 1964 assessment.

Curtin concluded that "in general the CFI system promises to be an extremely valuable tool of management and will provide many answers to management problems".

In the winter of 1964, the plots were again remeasured: (1) to provide data for this study, (2) to test the new computer programmes for analysing CFI data, and (3) to assess the status of the forest at the end of the first ten-year cutting cycle since the implementation of the management plan.

In this remeasurement, some additional data were collected, partly as a result of deficiencies indicated by this study. (1) To provide information on growing stock less than 4 in d.b.h., the number of saplings of desirable species in four mil-acre sub-plots in each plot was recorded in one-inch diameter classes. (2) To give the total basal area carrying capacity of plots, the basal area occupied by useless species not previously measured was estimated. (3) Damaged trees were classified according to type and severity of damage. (4) Further plot information was collected, especially with respect to treatment, logging and fire history.

The forest is now at the stage where the even-aged stands created about 1890 have reached maturity and are being harvested, and the peaked diameter-class distribution is largely masked by the inverted-J-shaped distribution typical of the selection forest. The smallest diameter classes (4-12 inches d.b.h.) are well represented, being derived from a period of deliberate encouragement of regeneration. The dominant stems in these classes are growing vigorously. The medium diameter classes (12-24 inches d.b.h.) are made up principally of the previously suppressed remnants of the even-aged stands and are deficient in number and growth rate. The largest diameter classes (24 inches d.b.h. plus) comprise the vigorous portion of the even-aged stands. They are well represented in number and most are still growing well.

The management policy now is to conserve as many as possible of the most vigorous mature trees until the small, fast-growing size classes reach merchantable size (16-20 inches d.b.h.). Thinning is carried out in these size classes to hasten the process. The forest is being deliberately undercut to build up the growing stock in the submerchantable classes. Because of the intensity of the silvicultural treatment, natural mortality is rare after the trees reach 4 inches d.b.h.

THE USE OF COMPUTERS IN THE ANALYSIS OF THE DATA

The initial processing of the 1957 and 1960 measurements was performed on an IBM 650 electronic computer (and later repeated on a 1401) which calculated the individual tree basal areas and volumes, and automatic card-handling equipment (sorter, tabulator, etc.) was used to give plot and forest summaries. The acquisition by the New South Wales Public Service Board of a Honeywell 400 computer gave the author the opportunity to write a programme which would do a similar operation, but would do all the processing on the computer, thus reducing card-handling to a minimum and producing a much more readable output. The 1960 and 1964 measurements were processed through this programme.

These plot summaries furnished the raw material for the regression analyses which followed. The differences between the 1957 and 1960 measurements gave the growth on the plots, which, when reduced to a per annum basis, provided the dependent variables, while the 1957 data furnished the independent variables for the analyses.

In order to eliminate immediately from consideration those independent variables which had little usefulness in explaining the variation in dependent variables, a "regression screen" computer programme was used. This programme was written by Dr G. M. Furnival[3] in 1962 for use on an IBM 709, on which some of the screening was carried out. The remainder was done on the Honeywell 400 using the same programme specialized for this machine by the author. The programme gives the coefficient of determination (R^2), i.e., the proportion of the total variation in the dependent variable explained by all desired combinations of the independent variables (18 in the programme's original form). Inspection of the values of R^2 makes it possible to assess the relative value of each independent variable.

The final stage of the analysis was the development of the multiple regression equations. The author has written a programme for the Honeywell 400 which prints out the partial regression coefficients, and also the covariance and inverse matrices which assist in statistically testing the equation. This programme was used to derive all equations developed.

Another programme which the author has written is designed specifically to calculate the growth rates of individual trees from successive measurements of CFI plots. These growth rates in terms of d.b.h., basal area and volume growth are sorted on selected plot and tree characteristics, are averaged and then printed out in species by size class tables. The results of this programme have assisted in the interpretation of the differences between the actual and predicted growth rates per acre in the present study.

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[3] Then Associate Professor of Forest Mensuration, School of Forestry, Yale University.

MULTIPLE REGRESSION ANALYSIS

In his analysis of the 1957-1960 growth period of the Coopernook CFI plots, Curtin (1962) did some preliminary graphical correlations of stand growth with various stand characteristics and suggested that multiple regression analysis techniques be used to determine the importance of these characteristics in various combinations.

The basic statistical theory of multiple regression has been well known for some time, and the essentials can be found in standard biological statistics texts such as Fisher (1958) and Snedecor (1956), or in some works on forest mensuration such as Schumacher and Chapman (1954) and Husch (1963). More comprehensive treatments of the techniques are given by Williams (1959) and Bliss (1963).

The status of multiple regression analysis, however, has had a fluctuating fortune. The danger of confusing a high correlation with a direct casual relationship is very real, and the famous example of the city where a high correlation was found between the number of nesting storks and the number of human births, must be continually kept in mind. Snedecor (1956) warns: "Some people seem to think that by some alchemy multiple regression will yield authentic information from careless measurements on heterogeneous material." There is no doubt that this type of interpretation of statistical evidence has led the field of statistics into disrepute; so much so that there has been a reactionary tendency by many research workers against regression and correlation analysis.

Recent developments in the philosophy of mathematical models has shed some new light on this controversy, and some aspects of the usefulness of model theory in forestry research have been indicated by Bakuzis and Brown (1962), and Jeffers (1964). Jeffers claims that three distinct types of mathematical models may be recognised, viz. descriptive models, predictive models, and decision models. The controversy is perhaps explainable in terms of confusion of these model types, in particular of the first two. For, as Jeffers points out, although descriptive models may be used for prediction, it frequently happens that one is required to predict outside of the range of the original data in which case special predictive models which differ somewhat from the descriptive models may be necessary. For instance if a growth relationship is known to be a sigmoid curve and extrapolation is likely outside of the range of the descriptive model which, say, is approximated by a straight-line relationship, then additional variables may be required in the predictive equation to approximate the sigmoid function.

This problem of extrapolation of the model to data beyond the original range has been another cause of suspicion of regression analysis. Regression equations have often been used with disastrous results on data which are completely out of context with that on which the equations were derived. However it may be legitimately argued that a predictive model which has no application outside of the original data has very little value. One of the aims of this study was to examine a case where a predictive model would be conservatively extrapolated.

Implicit in the word "model" is the idea of careful construction and painstaking planning. A model is not just a representation of the original, but a scaled-down version such that each part of it bears an exact relationship to the original part. Only if this is so, will the assembly of parts build a good model. Likewise, a good mathematical model is made up of parts which bear a close relationship to the respective parts of the described situation. A model used to observe a dynamic situation such as the growth of forest stands must be theoretically sound in all its parts and be based on the most accurate data available. Such models are likely to receive the approval of most research workers.

DEVELOPMENT OF PREDICTIVE MODELS

Preliminary Investigations

The annual net basal area and volume increments with and without ingrowth for each plot over the period 1957 to 1960 were calculated by the following formulae:

$$NGXI = (M_1 + R - M_0 - D - I)/Y \quad \ldots \quad (1)$$

$$NGWI = (M_1 + R - M_0 - D)/Y \quad \ldots \quad (2)$$

where

NGXI = net annual growth without ingrowth.

NGWI = net annual growth with ingrowth.

M_1 = basal area or volume at first remeasurement (1960).

R = basal area or volume removed 1957-60.

M_0 = basal area or volume at original measurement (1957).

D = mortality 1957-60 (basal area or volume).

I = basal area or volume ingrowth (1960).

Y = growth period in years.

The initial choice of possible independent variables was influenced by the following considerations:—

(1) The type and amount of data which had been collected in the original measurement. In general, this was quite comprehensive, although a few gaps became noticeable as the analysis progressed.

(2) Graphical analyses by Curtin (1962) and the author of various single independent variables plotted against growth.

(3) Various published works dealing with the factors which influence tree and stand growth, in particular those of Smith (1963), Baskerville (1962), Kozlowski (1962), Buckman (1962), and Jacobs (1955).

It seemed logical to investigate net basal area growth without ingrowth to begin with, since this would reduce some of the variability in the dependent variable by eliminating the factors of height (volume being a function of basal area and height) and ingrowth.

In the initial computer analysis, using the "full screen" programme, the following eighteen independent variables were tested:—

Basal area/acre.

Number of trees/acre.

Sum of diameters/acre.

Mean merchantable height.

Sum of diameters/acre × mean merchantable height.

Mean diameter.

Standard deviation of diameters.

Coefficient of variation of diameters.

Mean basal area per tree.

Percentage blackbutt by basal area.

Percentage blackbutt by number of trees.

Mean dominance class.

Percentage dominants and co-dominants by basal area.

Percentage dominants and co-dominants by number of trees.

Mean crown class.

Soil type.

Aspect.

Slope.

Basal area/acre, number of trees/acre and sum of diameters/acre are frequently used as stand density indicators in studies of this nature, since they are correlated with the amount of cambial area available for accretion of wood. In this respect, sum of diameters/acre × mean merchantable height (merchantable height being the height from ground to estimated cut-off point if the tree is mature, or to crown-break or four inches diameter if not mature) introduces the height factor to approximate bole area, although it is theoretically less valid than sum of (diameter × merchantable height). Mean merchantable height has also been used separately. Some of these variables, in particular number of trees/acre, may also be inversely correlated with average age of the stand, since in general the younger the stand the more trees present.

Mean diameter and mean basal area per tree, standard deviation of diameters and coefficient of variation of diameters have been included to attempt to describe the diameter-class distribution of the stand and, in particular the degree of even-ageness. The history of the forest indicates that some plots may be basically even-aged mature stands from the 1890s regeneration, while some may be even-aged sapling stands from the large openings of the 1950s. Both of these size-classes appear to be growing faster than the intermediate sizes.

Percentage blackbutt is used as a factor describing species composition. Because of blackbutt's importance in the stand with respect to numerical strength, desirability and superior growth rate, some measure of the proportion of this species seems desirable.

Mean dominance class, and percentage dominants and co-dominants are used to introduce the fact that dominants and co-dominants grow at a faster rate than the subdominant and suppressed stems. Similarly mean crown class is a variable which expresses that trees with good healthy crowns produce more wood than those with poor crowns, other factors being equal, of course (see Appendix 8).

Soil type, aspect and slope are site factors. Most of the forest is remarkably uniform in this respect, due mainly to the gentle topography and uniform geological history (see Appendix 8).

Following the investigation of basal area growth excluding ingrowth, the mean annual ingrowth for each plot was added to the basal area growth and the resultant basal area growth including ingrowth was analysed in the same way using the same independent variables, except that a few of the least useful ones, as indicated by the previous analysis, were dropped.

Since this showed a considerable decrease in the amount of variation explained by significant variables, basal area ingrowth itself was next investigated using the same basic list of independent variables but with the addition of four variables concerned with the stocking in the smallest measured size class (4 to 8 inches d.b.h.). These variables were:—

Number of stems in 4-8 inch class.

Ratio of number of stems in 4-8 inch class to total number of stems.

Basal area in 4-8 inch class.

Ratio of basal area in 4-8 inch class to total basal area.

The next stage was to investigate volume growth excluding ingrowth. Here, volume per acre was added to the basic list of independent variables. The similar analysis of volume growth including ingrowth gave R-square values close to those obtained when ingrowth was excluded, so that no separate analysis of volume ingrowth was needed.

Later on, sum of (diameter × merchantable height) and three variables suggested by Curtin's (1964) work on stand density in even-aged stands of *Eucalyptus obliqua* L'Herit. were tested against volume growth. These additional three were:—

Sum of (diameter squared).

Sum of (diameter × mean merchantable height squared).

Number of trees × mean merchantable height squared.

Curtin derived a Stand Density Index equation for even-aged eucalypt stands in which the most significant terms were D^2, DH^2 and H^2, where D is d.b.h. and H is the mean dominant height, and the terms of his equation are summed over all dominants and co-dominants in the stand.

If the definition of the mean dominant height of a stand in a group selection forest is accepted as the mean total height of mature dominant trees, this is a very different statistic to the mean dominant height of an even-aged stand. The former is the maximum height which can be produced on a site while the latter is the current status of this statistic at the current age of the stand. Thus it would be quite possible to have a half-acre plot in a group selection forest containing an essentially even-aged stand of saplings of which the current mean dominant height is, say, 30 feet, while the maximum mean dominant height is 120 feet.

Usually, however, on a half-acre plot there is a mixture of ages, and a "current mean dominant height" is indeterminate and indeed meaningless. Since there is usually a good correlation between mean dominant height and average total height in an even-aged stand, it would be logical to assume that "mean total height" of the irregular stand might approximate the factor. However, the total heights of the trees in the plots were not measured since the volume tables are based on merchantable height, and since measuring the total height of a eucalypt of 150 feet or so is very time-consuming and fraught with error due to the impossibility of seeing through the crown to its top. It was assumed that mean merchantable height would be sufficiently correlated with mean total height to substitute for it, and it was summed over all trees in the plot. The H^2 term then became $N.H^2$ (number of trees × mean merchantable height squared), where N is the number of trees, since H is constant for a plot.

Basal area growth and ingrowth

In the investigations of net basal area growth without ingrowth, it was found that number of trees/acre was the best single predictor, accounting for 60 per cent of the variation, and that 76 per cent of the variation in the dependent variable could be explained by number of trees/acre, percentage of blackbutt by basal area, and soil group. Additional variables from the above list were not statistically significant (see Appendix 9).

Since age in a forest of the nature of Coopernook is an indeterminate factor, it is difficult to separate it from stand density. This may explain to a large extent why number of trees/acre was more significant in the basal area growth regressions than other variables which are usually held to be better measures of stand density (e.g. basal area/acre explained 25 per cent of the variation in the dependent variable and sum of diameters/acre 54 per cent, compared with 60 per cent for number of trees/acre). In addition, when added to a regression containing number of trees/acre, these other variables could not explain any more variation than could the latter alone. Another characteristic of this variable was its strong linearity (see Appendix 2) throughout the range of the data (up to 184 stems/acre). It is also noteworthy that the high numbers of stems/acre were generally associated with fairly low basal areas and small mean diameters. All these factors suggest that number of trees/acre is more a measure of age than of stand density.

At first it was considered possible to differentiate four separate soil groups on the basis of colour, texture and depth. These were represented in the regression as three dummy variables. However, it was shown in the statistical analysis that some of the soil groups did not differ significantly (Table 1). Consequently the groups were re-formed into only two groups—Group A being the dark, deep, uniformly-textured soils, and Group B being the yellowish, shallow, gravelly soils and the water-logged soils. As shown by Table 2, these differed significantly.

The equation finally chosen for net annual basal area growth without ingrowth is:—

$$NGXI(BA) = -0.205 + 0.0216\,(NT) + 0.0154\,(\%BB) + 0.529\,(SGA) \quad (3)$$

where NT = number of trees/acre

%BB = percentage of blackbutt by basal area

SGA = Soil Group A = 1 if plot has Soil Group A

= O if plot has Soil Group B

The construction of a satisfactory prediction equation for basal area ingrowth proved difficult. The best equation containing only significant variables was found to be:—

$$I(BA) = 2{\cdot}08 - 0{\cdot}0806(MD) - 0{\cdot}00953(BAA) + 0{\cdot}403(SGA) \quad (4)$$

where

MD = mean diameter of trees on plot

BAA = basal area/acre

SGA = Soil Group A, as in equation (3)

TABLE 1

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR BASAL AREA GROWTH EXCLUDING INGROWTH (4 SOIL GROUPS)

$R^2 = 0{\cdot}758$ Constant term = —0·174

Variable	Partial regression coefficient	Standard error	t	Sign
Number of trees	0·0213	0·0018	12·2	**
Per cent blackbutt	0·0148	0·0033	4·4	**
Soil grp. 1—soil grp. 4	0·599	0·219	2·7	**
Soil grp. 2—soil grp. 4	0·532	0·210	2·5	*
Soil grp. 3—soil grp. 4	0·234	0·314	0·75	n.s.
Soil grp. 1—soil grp. 2	0·047	0·181	0·26	n.s.
Soil grp. 2—soil grp. 3	0·297	0·291	1·0	n.s.
Soil grp. 1—soil grp. 3	0·364	0·295	1·2	n.s.

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	5	58·1071
Residual	54	18·5689
Total	59	76·6760

Mean square residual = 0.3439

Root mean square residual = 0.578

N.B. In these Tables:—

** indicates significance at the 1 per cent level,

* indicates significance at the 5 per cent level, and

n.s. indicates non-significance at the 5 per cent level.

TABLE 2

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR BASAL AREA GROWTH EXCLUDING INGROWTH (2 SOIL GROUPS)

$R^2 = 0{\cdot}758$ Constant term = —0·205

Variable	Partial regression coefficient	Standard error	t	Sign
Number of trees	0·0216	0·0017	12·9	**
Per cent blackbutt	0·0154	0·0031	4·9	**
Soil grp. A—soil grp. B	0·529	0·169	3·1	**

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	3	58·1092
Residual	56	18·5668
Total	59	76·6760

Mean square residual = 0·3147
Root mean square residual = 0·561

This equation, however, explained only 34 per cent of the variation as shown by the statistical analysis in Table 3. Attempts to relate this growth component to the treatment of the stand which produced the regeneration now grown into the 4 inch minimum measured d.b.h., were frustrated by lack of precise data about the history of the plot sites prior to 1957 when the plots were established.

The variables used in the basal area ingrowth equation must be interpreted with some caution, due to the low coefficient of determination for the equation. However, it seems reasonable that high basal area ingrowth should be associated with small mean diameters and low basal areas since these would generally represent the more juvenile stands.

To predict net annual basal area growth with ingrowth, two approaches have been used. The first was to use equations (3) and (4) and then to add the results; the second was to derive a separate equation. The best equation involved the same independent variables as equation (3):—

$$\text{NGWI(BA)} = 0{\cdot}537 + 0{\cdot}217(\text{NT}) + 0{\cdot}0100(\%\text{BB}) + 0{\cdot}808(\text{SGA}) \quad (5)$$

As shown in Table 4, this explained only 53 per cent of the variation, and the term for percentage of blackbutt was not significant. However, because of its significance in equation (3) and its near significance in this equation, the term has been retained.

TABLE 3

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR BASAL AREA INGROWTH

$R^2 = 0{\cdot}339$ Constant term = 2·08

Variable	Partial regression coefficient	Standard error	t	Sign
Mean diameter	—0·0806	0·0215	3·8	**
Basal area/acre	—0·00953	0·00278	3·4	**
Soil grp. A—soil grp. B	0·403	0·191	2·1	*

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	3	11·517
Residual	56	22·360
Total	59	33·877

Mean square residual = 0·3993
Root mean square residual = 0·632

TABLE 4

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR BASAL AREA GROWTH INCLUDING INGROWTH

$R^2 = 0{\cdot}533$ Constant term = 0·537

Variable	Partial regression coefficient	Standard error	t	Sign
Number of trees	0·0217	0·0029	7·5	**
Per cent blackbutt	0·0100	0·0055	1·8	n.s.
Soil grp. A—soil grp. B	0·808	0·293	2·8	**

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	3	60·7558
Residual	56	53·1434
Total	59	113·8992

Mean square residual = 0·01583
Root mean square residual = 0·126

Volume Growth

Although basal area ingrowth makes up about a quarter on the average of the total net basal area growth, volume ingrowth comprises only about 8 per cent of the total net volume growth. For this reason, volume ingrowth was not investigated separately, but separate equations were developed for volume growth without and with ingrowth.

The best prediction equation for volume growth excluding ingrowth was:—

$$NGXI(V) = 43{\cdot}9 + 0{\cdot}00294(NH^2) + 2{\cdot}63(\%BB) + 116(SGA) \quad (6)$$

where

(NH^2) = number of trees × mean merchantable height squared.

This equation explained 91 per cent of the total variation (see Table 5).

Of the variables suggested by Curtin's (1964) work, the NH^2 variable alone explained 75 per cent of the total variation in the net volume growth without ingrowth variable, the DH^2 term explained 69 per cent and the D^2 term, 33 per cent. However, these are all highly correlated, and taking all three together in a multiple regression increased the coefficient of determination only to 76 per cent.

TABLE 5

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR VOLUME GROWTH EXCLUDING INGROWTH

$R^2 = 0{\cdot}907$ Constant term = 43·9

Variable	Partial regression coefficient	Standard error	t	Sign
Number of trees × mean merch. ht. squared.	0·00294	0·00016	18·4	**
Per cent blackbutt	2·63	0·49	5·4	**
Soil grp. A—soil grp. B	116·	27·	4·3	**

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	3	4,221,016
Residual	56	431,070
Total	59	4,652,086

Mean square residual = 7,698
Root mean square residual = 87·7

The superior predictive ability of the NH^{-2} term to the DH^{-2} term is in accord with the evidence that number of trees is a better predictor of basal area growth than any variable involving diameters. This suggested that perhaps NH^{-} (i.e. sum of the merchantable heights) would be a further improvement, the assumption being that the bulk of the volume growth is produced by the large trees which have a fixed merchantable height and consequently all their growth is due to basal area increment. Volume growth would then be a function of basal area increment and an average height, and NH^{-} should be the best predictor of this. This variable was in fact inferior to NH^{-2} ($R^2 = .62$ per cent) in predicting volume growth, at least part of the reason being that the relationship exhibited somewhat more curvilinearity (see Appendices 3 and 4 for graphs). In other words, squaring the merchantable height improves the weighting of the various trees by accentuating the faster growth of the taller trees.

The measure of stand composition used in both basal area and volume growth equations is percentage of blackbutt by basal area. The equation indicates that of two stands having the same NH^2 and on the same type of soil, a pure blackbutt stand will grow about 130 super feet Hoppus[4] more per annum or about 20 per cent more than a mixed stand containing only 50 per cent blackbutt by basal area. The importance of this variable in the models attests to the desirability of this species in the native forest of the future and substantiates the policy of encouraging its development and extension in this type of forest.

Very little research has been carried out on the soils in blackbutt forests. Florence (1961) had some evidence suggesting that the ecological distribution of blackbutt communities was more related to the physical structure of the soils than to their nutrient level. Since the grouping of soils in the present study was based on their physical characteristics, it would seem that the growth may also be more dependent on their physical, rather than chemical, structure. Certainly this would appear a fruitful field for research.

The best single predictors of volume growth with ingrowth were found to be number of trees × mean merchantable height squared, for which the coefficient of determination was 0·73, and sum of (diameter × merchantable height), for which R^2 was 0·66. In comparison, volume per acre explained only 34 per cent of the variation, while number of trees per acre explained 33 per cent.

Two equations have been developed for net volume growth with ingrowth, and the statistical analyses of these are given in Tables 6 and 7. The equations are:—

$$NGWI(V) = -44{\cdot}7 + 0{\cdot}0113(SDH) + 2{\cdot}38(\%BB) + 118(SGA) \quad (7)$$

and

$$NGWI(V) = 64{\cdot}9 + 0{\cdot}00291(NH^2) + 2{\cdot}47(\%BB) + 124(SGA) \quad (8)$$

---

[4] One super foot Hoppus equals 0·106 cubic feet.

TABLE 6

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR VOLUME GROWTH INCLUDING INGROWTH

$R^2 = 0{\cdot}738$ Constant term = —44·7

Variable	Partial regression coefficient	Standard error	t	Sign
Σ(d.b.h. × merch. ht.)	0·0113	0·0017	6·7	**
Per cent blackbutt	2·38	0·80	3·0	**
Soil grp. A—soil grp. B	118·	44·	2·7	**

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	3	3,425,407
Residual	56	1,214,900
Total	59	4,640,307

Mean square residual = 20,592
Root mean square residual = 143

TABLE 7

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR VOLUME GROWTH INCLUDING INGROWTH

$R^2 = 0{\cdot}885$ Constant term = 64·9

Variable	Partial regression coefficient	Standard error	t	Sign
Number of trees × mean merch. ht. squared.	0·00291	0·00017	17·2	**
Per cent blackbutt	2·47	0·33	4·7	**
Soil grp. A—soil grp. B	124·	29·	4·4	**

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	3	4,105,359
Residual	56	534,948
Total	59	4,640,307

Mean square residual = 9,067
Root mean square residual = 95·2

Equation (7) has the sum of (diameter × merchantable height), which is related to bole area (Lexen, 1943) or the amount of cambial surface area available for the production of new tissue, as its primary variable. Equation (8) for the same dependent variable has number of trees x merchantable height squared, which is rather more difficult to explain rationally but which accounts for considerably more of the variability, as the principal variable. The reason for developing two equations was to ascertain whether the use of a more biologically rational variable compensated for a decrease in the coefficient of determination from 0·89 for equation (8) to 0·74 for equation (7). In both equations the secondary variables are the percentage of blackbutt by basal area, and the soil groups.

The highly significant linearity of the primary variables, SDH and NH^2, in these equations can be best explained when it is recognised that probably none of the CFI plots, with the possible exception of one, are carrying sufficient growing stock to achieve maximum volume increment. The possible exception is a plot which is partly in a research control plot; this research plot is in an even-aged stand dating from 1932 and has had no silvicultural treatment. This CFI plot had a periodic annual increment of almost 1,900 super feet/acre between 1957 and 1960, and had a mean annual increment of 880 super feet/acre in 1957 increasing to 1,040 in 1960, indicating a probable maximum around 1,200 super feet/acre. None of the other plots achieved a periodic growth rate of 1,100 super feet/acre between 1957 and 1960, although a few of them exceeded this in the subsequent period.

There are other indications that the plots are understocked: the linearity of the relationship between number of trees per acre and basal area increment, and the paucity of natural mortality, are two. This understocked condition with respect to maximum volume increment is not necessarily to be deprecated; partly it is by design. The policies of treatment to remove useless vegetation, heavy thinning to encourage rapid passage of saplings into the deficient middle classes, and large regeneration openings to favour blackbutt, have resulted in a forest which on the whole is temporarily understocked, so that as the gaps fill up there will be a significant improvement in the quality of the forest. There are of course other reasons for low stocking on particular plots, even apart from site differences; in particular the amount of understorey and ground flora, which is often a reflection of the fire history, may significantly affect the stocking of trees. In 1964 the basal area of understorey species was measured, and on a few plots approached 20 square feet per acre.

In such an understocked forest, it is not unreasonable to assume that the amount of increment accruing to the trees is related to the amount of light and nutrient energy being received by them. If this is so, the trees with the largest crowns and root systems, assuming trees of similar efficiency for capturing and converting this energy, will be adding on the most increment. The diameter growth figures in Table 13 to some extent support this hypothesis. The two measures of tree size used in the equations for volume growth are diameter × merchantable height, and merchantable height squared. Both of these have area dimensions, and it is not inconceivable that they would be related to effective leaf area.

It is interesting to note that the consolidation of the four soil groups to two increased the value of R^2 from 0·824 to 0·885 for equation (8), but reduced it from 0·751 to 0·738 for equation (7).

The lack of significance of the variables describing the diameter-class distribution may have been due to a poor choice of variables, although neither Nelson (1964) nor Buckman (1962) using these and other variables could obtain a significant term to express this factor in their regression equations for the growth of even-aged stands. As suggested later, a factor which deals with only that portion of the distribution of greatest interest may be more useful.

The variables dealing with the characteristics of individual trees, viz. dominance and crown classes, did not prove significant. Normally these factors do not vary greatly between stands, unless some external influences, e.g. cutting or disease, have disturbed the structure of the stand. It would not be expected that the marked influence that these factors have on the growth of individual trees would show up in the growth of stands, since compensating factors would tend to obscure the individual-tree relationships.

As anticipated, neither slope nor aspect in this small forest of rolling terrain showed as significant in any of the regression equations.

In order to obtain a means of estimating net useful volume growth, useful volume being that volume classified as potentially saleable, a linear regression equation was developed so that this could be estimated from net total volume growth, as predicted from equation (7) or (8). Since equation (8) explains a greater amount of the variation in total volume growth than equation (7), it is used here to predict useful volume growth. The statistical analysis of this equation is given in Table 8; there is a high correlation ($R^2 = 0·96$). The equation is:—

$$NGWI(UV) = 27·5 + 0·893\,(NGWI(V)) \quad \ldots \quad (9)$$

However, the constant term had a standard error of 16·1, indicating that the constant did not significantly differ from zero, so the equation was recomputed to give the simplified equation:—

$$NGWI(UV) = 0·929\,(NGWI(V)) \quad \ldots \quad (10)$$

In other words, approximately 93 per cent of the net volume growth is in useful or potentially useful volume.

An interesting feature of the independent variables used in the equations developed is their large degree of true independence. In pure even-aged stands, it is usually considered that the effects of stand density, age, and site are reasonably independent, and for mixed stands, species composition might be added. In the equations developed here for basal area growth and volume growth, the first variable is primarily a measure of stand density or age, the second variable indicates species composition and the third is a measure of site.

TABLE 8

STATISTICAL ANALYSIS OF REGRESSION EQUATION FOR USEFUL VOLUME GROWTH INCLUDING INGROWTH

$R^2 = 0{\cdot}962$ Constant term = 27·5

Variable	Partial regression coefficient	Standard error	t	Sign
Total volume growth as predicted by eqn. (8).	0·893	0·023	38·2	**

Analysis of Variance

Source	Degrees of freedom	Sums of squares
Due to regression	1	4,433,433
Residual	58	177,483
Total	59	4,610,916

Without Constant

Variable	Partial regression coefficient	Standard error	t	Sign
Total volume growth as predicted by eqn. (8).	0·929	0·010	89·	**

TESTING THE EQUATIONS

The CFI plot summaries for the 1960 remeasurement of Coopernook gave the necessary independent variables for predicting the net annual basal area and volume growth for the next growth period. These predicted values for each plot are given in Appendix 5.

After the plots were again remeasured in 1964 it was possible to calculate the actual net annual basal area and volume growth for each plot as well as for the forest as a whole. These could then be compared with the predicted values. The actual growth rates are also shown in Appendix 5.

The standard errors of the estimated mean growth rates of the forest were also calculated, and are shown in Table 9. It can be seen that the only equation which predicts the mean growth within the 95 per cent confidence limits (predicted mean $\pm$ 2.00 $\times$ S.E.) is equation (3) for net basal area growth excluding ingrowth. This test is, however, unduly restrictive in that it does not take account of the desired level of precision, or of the degree of dispersion in the test sample. It does indicate that there is a consistent bias in all predictions except when equation (3) is used, the predicted values being less than those actually observed.

TABLE 9

COMPARISON OF ACTUAL AND PREDICTED MEAN GROWTH RATES

Eqn. No	Dependent Variable	Mean Growth Rates		Standard Error of Pred. Mean
		Actual	Predicted	
		(square feet/acre/year)		
(3)	B.A. growth excluding ingrowth ..	2·88	2·89	0·07
(4)	B.A. ingrowth	1·34	0·63	0·08
(3) + (4)	B.A. growth including ingrowth ..	4·22	3·52	..
(5)	B.A. growth including ingrowth ..	4·22	3·45	0·13
		(super feet Hoppus/acre/year)		
(6)	Volume growth excluding ingrowth	663·	596·	11·
(7)	Volume growth including ingrowth	708·	624·	19·
(8)	Volume growth including ingrowth	708·	609·	12·
(8), (10)	Useful volume growth including ingrowth.	683·	566·	..

Another test that might be used and which does take into account the variation in the test sample, is the t-test of paired replicates. As indicated in Table 10, this shows fairly good agreement with the test of the means, in that equation (3) is the only equation which predicts values which are not significantly different from those actually obtained. However, where there are wide and erratic differences between observed and predicted values, a large bias can be obscured in this test (Freese, 1960), and this is undoubtedly the reason for the near non-significance in the cases of equations (6) and (7).

TABLE 10

T-TEST OF DIFFERENCES BETWEEN MEANS OF ACTUAL AND PREDICTED GROWTH RATES

Eqn. No.	Dependent Variable	Mean Difference (act.-pred.)	Standard Error of Mean Diff.	t	Sign
		(square feet/acre/year)			
(3)	B.A. growth excluding ingrowth	—0·02	0·12	0·17	n.s.
(4)	B.A. ingrowth	0·74	0·14	5·3	**
(3) + (4)	B.A. growth including ingrowth	0·73	0·21	3·5	**
(5)	B.A. growth including ingrowth	0·75	0·23	3·3	**
		(super ft. H./acre/year)			
(6)	Volume growth excluding ingrowth	66·	33·	2·0	*
(7)	Volume growth including ingrowth	86·	37·	2·3	*
(8)	Volume growth including ingrowth	98·	34·	2·9	**
(8), (10)	Useful volume growth including ingrowth	117·	36·	3·3	**

A test which permits the specification of a desired level of precision is the chi-square test, using the formula in the form given by Freese (1960):—

$$\chi^2(n)df = \frac{196^2}{p^2} \sum_{i=1}^{n} \left(\frac{d_i}{\mu_i}\right)^2$$

where n = number of plots.
p = desired level of precision as a percentage.
d_i = difference between actual and predicted value for plot i.
μ_i = actual value for plot i.

Where one is predicting something as inherently variable as the growth on individual plots, it may not be unreasonable to accept such tolerant limits as ± 100 per cent at the 95 per cent confidence level. It was found, however, that even at this level of precision the tabular value of chi-square was greatly exceeded in all cases. Inspection of the contributions of individual plots to the chi-square value revealed that a few plots contributed excessively and disproportionately. The plot record sheets showed that a severe wild-fire had burnt through four of the plots less than a year before the remeasurement in 1964, and the consequent loss of bark combined with the probable loss of increment due to defoliation had caused negative or abnormally small growth rates to be recorded.

When these four plots were removed from the test, there was a considerable improvement in the chi-square values despite the loss of four degrees of freedom. All growth rates, except basal area ingrowth, could be predicted well within the 100 per cent level of precision, and most of the equations predicted growth rates for individual plots within 60 per cent of the actual value, at the 95 per cent confidence level. The chi-square values are tabulated in Table 11 for 50 per cent and 60 per cent and 100 per cent levels of precision.

TABLE 11

CHI-SQUARE TEST OF ACTUAL AND PREDICTED GROWTH RATES

Eqn. No.	Dependent Variable	χ^2 for level of precision =		
		±50%	±60%	±100%
(3)	B.A. growth excluding ingrowth ..	78·2	56·6	19·5
(4)	B.A. ingrowth	1158·6	804·5	289·5
(3) + (4)	B.A. growth including ingrowth ..	117·7	81·6	29·4
(5)	B.A. growth including ingrowth ..	133·6	92·5	33·4
(6)	Volume growth excluding ingrowth	81·6	56·6	20·4
(7)	Volume growth including ingrowth	90·5	55·3	22·6
(8)	Volume growth including ingrowth	76·2	52·9	19·0
(8), (10)	Useful volume growth including ingrowth.	71·0	49·2	17·7

Critical level of $\frac{\chi^2}{56 \text{ d.f.}}$ = 74·5 at 5 per cent level.

COMPARISON WITH STAND-TABLE PROJECTION METHOD

Some idea of the value of the regression model method for predicting the mean volume growth per acre of the forest can be gained by comparing its predicted value with that obtained by the alternative method of stand-table projection.

The technique of stand-table projection used was the straight-forward method described by Husch (1963) and other mensurationists. No refinements were used since all that was required was some idea of the order of accuracy of the method. Four-inch size classes were used, with the 4-8 inch class the smallest and 28 inch+ being the largest.

The details of the stand-table projection are given in Appendix 6. Two projections have been performed; they differ in the diameter growth rates used. The first table uses the growth rates obtained by Curtin (1962) for the period 1957 to 1960 on the CFI plots. The second table uses the growth rates used in the 1954 Management Plan for Coopernook State Forest for yield calculations. These latter growth rates, based on measurements of several sample plots of various types on the forest, may be considered the best available estimates of diameter growth prior to the availability of CFI data.

The results are summarized in Table 12. Whereas the regression model method underestimated the volume growth by 12 per cent, the stand-table projection method using CFI growth data overestimated the growth by 11 per cent, and using the management plan data overestimated it by 26 per cent.

TABLE 12

COMPARISON OF VOLUME GROWTH AS PREDICTED BY REGRESSION MODEL AND STAND-TABLE PROJECTION METHODS

	Actual Values	Predicted values by		
		Eqn. (7)	Stand-table projection	
			CFI	Management plan data
	(Volumes in super feet Hoppus)			
Average total volume/acre (1960)	16,191	16,191	16,191	16,191
Average total volume/acre (1964) (assuming no removals or mortality)	19,377	18,999	19,743	20,199
Average volume growth 1960-64	3,186	2,808	3,552	4,008
Actual-predicted	..	378	—366	—822
Percentage error	..	12%	11%	26%

DISCUSSION

The primary purpose of the technique being investigated is its ability to predict the growth of the forest, and the results are therefore first examined in this light.

The equation developed to predict basal area growth excluding ingrowth (equation (3)) was very successful, the difference between the actual and predicted values being almost negligible.

The predictive ability of the equation for basal area ingrowth (equation (4)) was very poor, as was expected from its low coefficient of determination. In the future it should be possible to develop a much better model for this variable, since data will be available on the development of the ingrowth from the time of its regeneration to its entry into the 4-8 inch size class.

Almost all of the bias in the predictions for mean basal area including ingrowth can be attributed to the difficulty of predicting the ingrowth component. There was little difference between calculating the predicted value by the specially derived equation (equation (5)) and estimating it by summing the values calculated by the equation for basal area excluding ingrowth (equation (3)) and that for basal area ingrowth (equation (4)).

The difference of 10 per cent between the actual and predicted mean volume growth excluding ingrowth was unexpected in view of the high coefficient of determination with this equation (equation (6)) and the success in predicting basal area excluding ingrowth. Since the primary variable in this equation is number of trees × mean merchantable height squared, a change in this relationship between the mean merchantable height of a plot and the volume growth on the plot was considered a possible explanation.

Examination of the size-class distributions of the trees for 1957, 1960 and 1964, and the average d.b.h. growth rates by size classes over this period indicate that such a change may well have occurred. These figures are given in Table 13, and the size class distributions are graphed on a semi-logarithmic scale in Appendix 7.

TABLE 13

CHANGES IN DIAMETER DISTRIBUTION AND DIAMETER GROWTH

D.b.h. Class in inches	Total number of trees/acre			D.b.h. growth in inches/tree/yr.	
	1957	1960	1964	1957-60	1960-64
4-8	28·3	35·5	67·2	0·36	0·26
8-12	14·0	13·3	14·3	0·25	0·29
12-16	8·3	8·4	9·5	0·26	0·29
16-20	6·4	5·7	5·7	0·25	0·30
20-24	4·7	4·5	4·5	0·28	0·33
24-28	4·4	3·8	3·4	0·29	0·33
28+	2·2	3·0	3·5	0·46	0·39

The most striking features of the size-class distribution figures are (1) the build-up of the 28 inch + class at the expense of the 24-28 inch class, and (2) the large increase in the number of stems in the 4-8 inch size class between 1960 and 1964. The first feature must be attributed to the deliberate policy instituted in 1962 to save the prime 28 inch + trees and to compensate for them by cutting more of the 24-28 inch trees. The saving of more 28 inch+ trees, some of which are undoubtedly not growing as fast as those previously saved, has decreased the diameter growth rate, but it is still the fastest growing size class. The second feature is probably due to the significant increase in the amount of ingrowth occurring during the 1960-1964 period, causing a reduction in the growth rate of this size class because of competition, and therefore reducing the number of trees entering the 8-12 inch size class. This is substantiated by the decrease in d.b.h. growth rate in the 4-8 inch class from 1960 to 1964. At the same time there have been significant increases in the average diameter growth rates in the intermediate size classes.

The precise effect of these changes in the diameter class distribution and the growth by size classes on stand variables and the growth of the stands is not easy to determine. One likely effect is a decrease in the mean merchantable height due to the greater proportion of small trees. Since height is squared in the NH^2 term, the increased number of trees may not be sufficient compensation for the H^2, and the value of the NH^2 term may be less for a given volume growth value. This may be accentuated by the increased growth of the intermediate size classes.

Until the forest reaches a condition much closer to all-aged than it is at present, such variations in diameter distribution and diameter growth distribution can be expected. It will therefore be necessary to account for these vagaries in the regression models if the latter are to be improved. It was noted that all the plots which had low predicted volume growth but normal basal area growth, had diameter class distributions in which 95 per cent or more of the trees were less than 20 inches d.b.h. This lends support to the theories above and suggests that useful variables may be found in the number or proportion of trees in the smaller size classes.

The two equations for volume growth including ingrowth (equations (7) and (8)) underestimated the mean value by 12 per cent using the equation with sum of (diameter × mean merchantable height), and by 14 per cent with the equation containing the NH^2 term. The effect of ingrowth on the prediction of volume growth has been to increase the error of the mean from 10 to 14 per cent. Since the equation with the SDH term (equation (7)) has a lower percentage error, it can be assumed that using this term in an equation to predict volume growth excluding ingrowth would have given a slightly better predictive equation. The difference is not very great, but does indicate that the R^2 value of a variable need not be the only criterion for its use in a predictive equation. The better performance of equation (7) suggests it may have more general application for other growth periods of this forest and for other forests than equation (8) which happened to have a closer relationship with the volume growth of this forest from 1957 to 1960. The reason for this may be the relationship of SDH to the cambial surface of the bole.

It was expected that the error associated with the prediction of useful volume growth would be greater than that for total volume growth, since it receives error components from two equations, viz. equations (8) and (10). However, it was noticed that in several plots, the useful volume growth exceeded the total growth, an anomaly caused by the trees classified as useless in 1957 being reclassified as useful in 1960. It is evident that the 50 per cent increase (12 per cent to 18 per cent) in the mean bias is attributable to a significant change in utilisation standards over the measurement periods.

Another effect which is not accounted for in the present models is the changes which occur in the stand structure following partial cutting. Since no quantitative information was available on the amount and time of cutting on the plot sites prior to 1957, it was not possible to include these factors as variables in the regression models. Inclusion of variables concerning removals in the 1957-1960 period were not used since these would have required the prediction of time, place and amount of removals over the period of growth prediction—this being almost as difficult as the growth prediction itself. Future models could include variables built up from data on the removals in the previous measurement period.

Since the prediction of basal area growth without ingrowth was so successful, it would seem that better volume growth models might be developed by using basal area increment as one of the variables. This approach was not used initially because there did not appear to be a high correlation between the two types of increment, and in any case the equations developed for volume growth had encouragingly high coefficients of determination.

The chi-square tests of the differences in growth rates between individual plots indicate that most of the types of growth can be predicted with an accuracy between 50 and 100 per cent on individual plots, provided plots which have been recently burnt are excluded from the sample. From this it appears that this technique is very far from the stage of refinement at which it might be used to predict the growth of individual plots. However, the purpose at hand is that of predicting the growth of whole forests.

The comparison of the regression model method with the stand-table projection method indicates that they are of comparable precision for predicting total volume growth per acre, the regression model method underestimating the growth by 12 per cent and the stand-table projection method overestimating it by 11 per cent. The advantage of having accurate growth data to use in the stand-table projection method is amply demonstrated in the comparison of the two stand-table projections. The use of CFI growth data in place of the best estimates otherwise available reduced the error from 26 per cent to 11 per cent.

The multiple regression method has some theoretical advantages over the methods based on tree diameter growth, in that it is related to plot growth and hence can incorporate into the growth prediction some of the complex effects of the dynamics of the stands. Because of this and because the method depends on isolating the major factors affecting stand growth, it can be very useful in pointing out where information is lacking.

In this instance, the lack of information about the stocking and growth rates of trees in the 0-4 inch size classes caused serious difficulties with the prediction of ingrowth. This is a common failing of most methods of forest growth prediction and one which can hardly be solved unless observations are extended to diameter classes smaller than those of the threshold diameter at which ingrowth is deemed to take place. There also appears to be need for more precise information about the way in which soil differences affect stand growth.

This method of analysis, like others, would doubtless work better in those ideal forests in which all age-classes are equally represented. In this investigation, equations derived from observations of an irregular, uneven-aged forest at one stage of development were tested against observations made in the same forest but in the immediately following stage of development. The cuttings that had gone on in the interim were aimed at altering the diameter class distribution to favour the 24-28 inch diameter class, at the same time generally aiming towards the theoretically ideal J-shaped distribution. Attempts have been made in this study to compensate for irregularity of diameter class distribution by testing parameters of this distribution. Some of the equations include terms which are thought to make partial correction for corresponding irregularities in the relationship between diameter growth and diameter itself. Further efforts along these lines are clearly necessary.

The results of this investigation also suggest that the parameters of stand density which show a reasonably good relationship to stand growth in even-aged stands are not as useful when applied to irregular stands.

It is probable that the method of growth prediction described here will always be subject to some error because of those effects, such as departures from the climatic norm[5], sporadic damage from fire and other agencies, improvements in management practices, and changes of utilisation standards, which are virtually impossible to predict.

The regression model method has a practical advantage over the stand-table projection methods in that it does not require growth information about individual trees. The facility with which tree growth data could be obtained by stem analysis gave rise to the stand-table projection method, but, when dealing with species lacking prominent growth rings, this type of information can only be obtained at some cost. In fact it has only been made practical by the computer analysis of CFI plots.

It must be considered, then, that the predictive model technique is preferable to the stand-table projection approach in the type of forest under consideration.

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[5] In this study, it is unlikely that climatic effects have appreciably affected the results. Although the mean annual rainfall for 1957-60 was 64 in and for 1960-64 was 71 in, the average number of wet days was 140 in the first period and 130 in the second.

SUMMARY AND CONCLUSION

The subjection to intensive multiple regression analysis of the data from CFI plots on an irregular eucalypt forest has shown that it is possible to develop regression models which explain a considerable amount of the variation in stand growth factors.

The equations developed for the various types of growth are as follows:—

1. Basal area growth excluding ingrowth:
$$NGXI(BA) = -0{\cdot}205 + 0{\cdot}00216(NT) + 0{\cdot}0154(\%BB) + 0{\cdot}529(SGA) \quad .. \quad .. \quad (3)$$

2. Basal area ingrowth:
$$I(BA) = 2{\cdot}08 - 0{\cdot}0806(MD) - 0{\cdot}00953(BAA) + 0{\cdot}403(SGA) \quad (4)$$

3. Basal area growth including ingrowth:
$$NGWI(BA) = 0{\cdot}537 + 0{\cdot}0216(NT) + 0{\cdot}0100(\%BB) + 0{\cdot}808(SGA) \quad .. \quad .. \quad (5)$$

4. Volume growth excluding ingrowth:
$$NGXI(V) = 43{\cdot}9 + 0{\cdot}00204(NH^2) + 2{\cdot}63(\%BB) + 116(SGA) \quad (6)$$

5. Volume growth including ingrowth:
$$NGWI(V) = -44{\cdot}7 + 0{\cdot}0113(SDH) + 2{\cdot}38(\%BB) + 118(SGA) \quad (7)$$
$$NGWI(V) = 64{\cdot}9 + 0{\cdot}00291(NH^2) + 2{\cdot}47(\%BB) + 124(SGA) \quad (8)$$

6. Useful volume growth including ingrowth:
$$NGWI(UV) = 0{\cdot}929\,(NGWI(V)) \quad .. \quad .. \quad .. \quad (10)$$

In each equation except the last, the independent variables used were those which were statistically significant and together explained the most variation. More than twenty independent variables were tested. In the equations for basal area and volume growth, the three selected variables are generally considered to exhibit a strong degree of mutual independence; this fact lends considerable support to the legitimacy of the technique.

Most of the variation in these equations was explained by the first variable, i.e., number of trees/acre for basal area growth, and number of trees × mean merchantable height squared and sum of (diameter × merchantable height) for volume growth. The strong linearity of these relationships is apparently due to the understocked condition of the stands.

These equations were used to predict the mean growth of the forest and the growth of individual plots during the next measurement period, and the predicted values were compared with the growth rates which actually occurred during this period.

It was found that the equation for basal area growth excluding ingrowth predicted the mean growth rate within 1 per cent of the actual value, and it must be concluded that this is a very adequate model for this aspect of stand growth. Mean basal area ingrowth, however, was very poorly predicted, the predicted value being almost 50 per cent less than the actual mean, and suggestions have been made concerning the type of data necessary for improving this model. Since ingrowth comprised about 25 per cent of the basal area growth including ingrowth, the effect of including ingrowth was to increase the percentage error to about 17 per cent.

The equation for volume growth excluding ingrowth underestimated the mean growth rate by 10 per cent. Examination of the diameter class distributions revealed that significant changes had occurred over the period, and it is probable that these have caused the error in volume prediction. Inclusion of volume ingrowth caused only a small increase in the percentage error, since ingrowth comprised less than 10 per cent of the volume growth including ingrowth. There was little to choose between the two equations for this type of growth; in fact the equation with the lower R^2 value predicted the mean slightly better than the alternative model.

The prediction of mean useful volume growth differed from the actual mean by about 18 per cent. Because this is derived from total volume growth it carries the error component associated with the model for volume growth including ingrowth; the additional error is undoubtedly due to changes in utilisation standards over the period of observation.

The percentage error associated with the prediction of the growth rates on individual plots was substantially reduced by taking into consideration the loss of increment on a few plots due to burning. However, the error was still high (between 60 and 100 per cent), and the accurate prediction of the growth of individual plots by this method would require a somewhat more refined technique.

The principal alternative to the proposed technique for the prediction of the future growth of an irregular forest is the stand-table projection method. This method was used to predict the volume growth over the same period and using the same basic data as for the predictive equations. The result was an overestimate of the mean volume growth rate by 11 per cent, which is comparable with the 12 per cent under-estimate given by the regression equation. When the same method was used with growth data which were the best available estimates other than CFI data, the overestimate increased to 26 per cent. The value of CFI is obvious from this.

It has been suggested that future measurements of the CFI plots should collect information on the stocking in the 0-4 inch d.b.h. size class, so that the basal area ingrowth model may be improved. This suggestion was actually implemented in the 1964 measurement, and the next remeasurement will provide information on the progress of trees from seedlings to the sapling stage. It has also been suggested that further research into the effects of soil characteristics and stand density parameters on the growth of stands of this type is urgently needed.

The result of these investigations has been to develop mathematical models which describe the various aspects of the growth of irregular eucalypt stands in terms of the stand parameters which have the greatest influence on the growth characteristics. In general these models explain a considerable part of the variation in the basal area and volume growth rates. These models can be used to predict future growth rates with an accuracy at least comparable to the more usual stand-table projection method, without the necessity of the latter method for data on the growth of individual trees.

The application of these models to eucalypt forests other than that under scrutiny in this study would depend on the degree of similarity between these forests and Coopernook State Forest. Most likely the regression coefficients would be different, even for a quite similar forest; quite probably the most significant parameters in the models would be different. This investigation has provided a lead to the types of independent variables worthy of consideration, has assembled the tools, and has demonstrated that the technique gives good results when used to predict future growth rates.

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APPENDIX I

FIELD PROCEDURE FOR INSTALLATION, MAINTENANCE AND REMEASUREMENT OF CFI PLOTS ON COOPERNOOK S.F.

The plots were 5 chains × 1 chain with steel pegs at every chain along the centre line. Trees were marked with a white paint mark at the point of measurement of d.b.h. Despite the clear marking of the plots in the field, Curtin (1962), after three years was not able to detect any bias in the tree-marking of the plots. The position of each tree greater than 4 in d.b.h. in the plot was plotted on graph paper, to facilitate re-identification, and each was assigned a number. Although, as Beers (1963) has indicated, individual tree identification is not necessary to obtain precise growth information, the system has been retained in New South Wales because it provides a means of checking each item of data against that collected at the previous measurement, thus reducing the possibility of errors.

Each tree was described according to its species, merchantability class, vigour class, diameter breast height over bark, and merchantable height.

All species of trees on the plots were measured with the exception of those species of no possible commercial value, such as *Casuarina* and *Acacia* spp.

The merchantability class was determined by the tree's probable fate. Such classes as sawlog, salvage log, pole, sleeper and useless were recognised.

The vigour classification used was the British three-digit system, in which the first digit was a dominance class (four classes), the second was a stem class (three classes), and the third was a crown class (three classes).

D.b.h.o.b. was measured with a tape to the nearest tenth of an inch.

The merchantable heights of most useful mature trees were measured with a Hagameter. The heights of other trees were usually estimated. In a useful mature tree the merchantable limit was the estimated point of cutting of the log, in useless mature trees it was the point of crown break, i.e. the point at which permanent bifurcation causes a marked reduction in the size of the main stem, and in immature trees an average height for the size class was generally used.

Volumes were calculated by the computer using a single two-way tree volume table for all species.

Each plot was described according to its aspect, slope, soil, site quality and mean dominant height, as well as location.

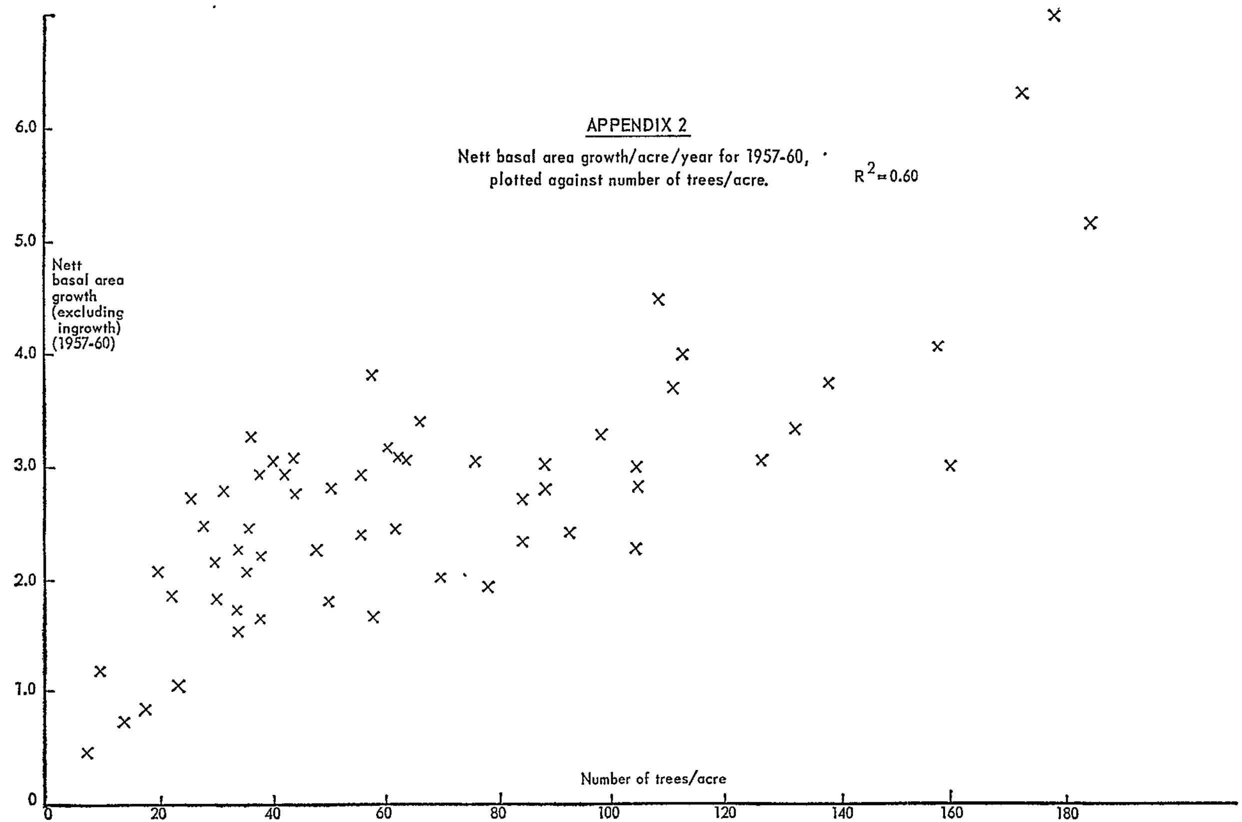
Prior to any logging or treatment likely to affect a particular plot, it is measured, and following the operation, those trees which have been removed are noted, together with their reason for removal. If the trees removed are sold, their log dimensions are noted. This time-consuming process is considered essential at this experimental stage of CFI in the state, since it allows the only possible check on the reliability of the merchantability classifications, of the estimates of merchantable height, and of the volume tables.

Remeasurements of all the plots are carried out periodically, using the computer listings from the previous measurement in such a way that each new piece of data is recorded immediately under that of the previous measurement, ensuring a high degree of field accuracy. Ingrowth is recorded separately.

The 1964 remeasurement added new information in the form of data on damage to individual trees, regeneration and stocking in the under-4-inch size class, and on the basal area of non-commercial species.

APPENDIX 2

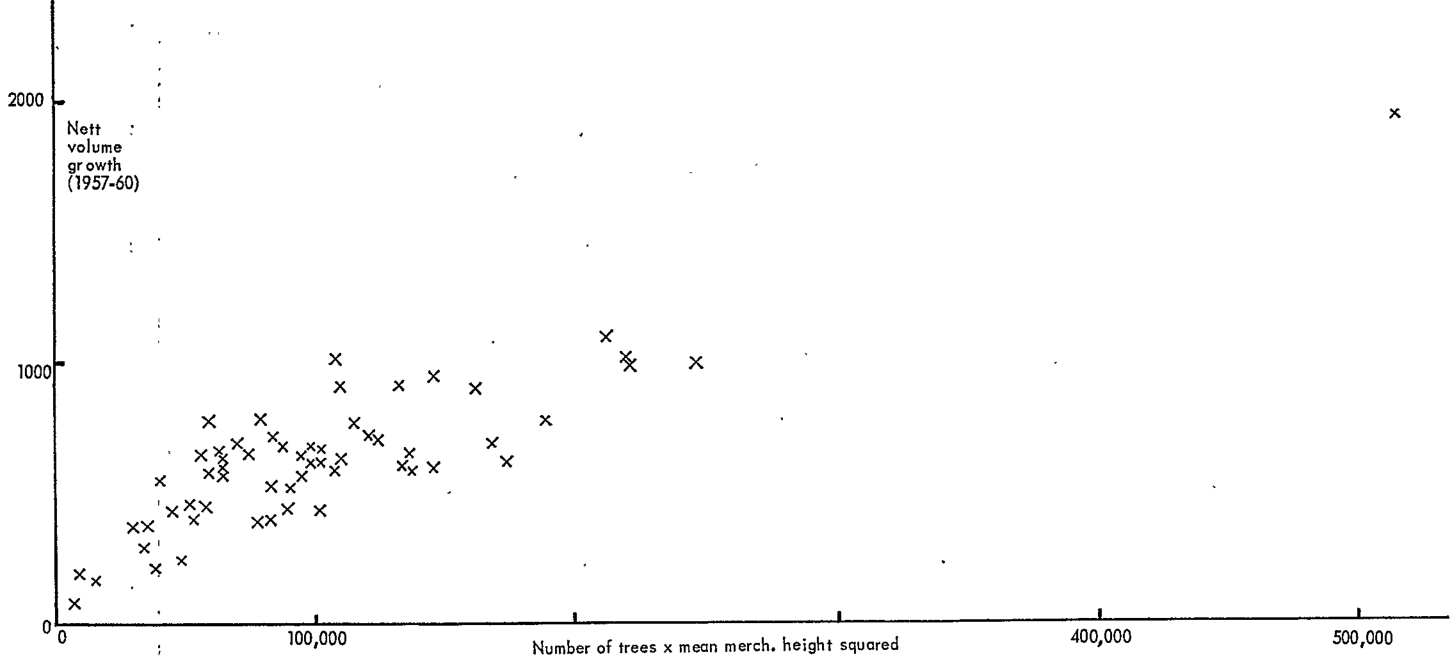
Nett basal area growth/acre/year for 1957-60, plotted against number of trees/acre.



APPENDIX 3

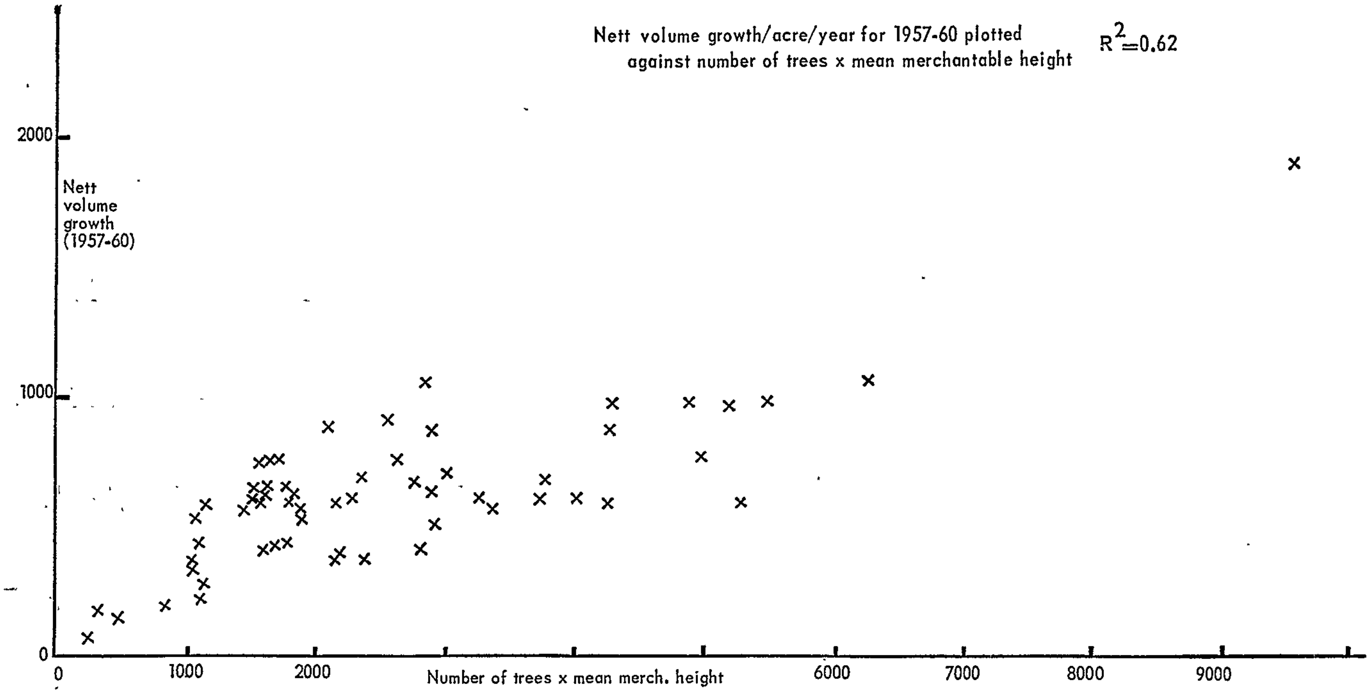
Nett volume growth/acre/year for 1957-60, plotted against number of trees x mean merchantable height squared.

$R^2 = 0.75$



APPENDIX 4

Nett volume growth/acre/year for 1957-60 plotted against number of trees x mean merchantable height $R^2 = 0.62$



APPENDIX 5

ACTUAL AND PREDICTED GROWTH RATES BY PLOTS (1960-64)

A. Basal area growth in square feet/acre/year.

Plot No.	B.A. Growth ex. Ingrowth		B.A. Ingrowth		B.A. Growth including Ingrowth		
	Actual	Predicted	Actual	Predicted	Actual	Predicted by addtn.	Predicted by eqn. (5)
1	1·9	2·5	0·4	0·4	2·3	2·9	3·0
2	1·5	1·8	0·1	0·7	1·6	2·5	2·7
3	0·9	2·1	0·8	0·5	1·7	2·6	2·6
4	2·5	2·8	2·0	1·0	4·5	3·8	3·6
5	2·2	4·2	0·1	0·3	2·3	4·5	4·9
6	3·8	3·2	1·0	0·9	4·8	4·1	3·6
7	0·6	2·7	1·2	0·4	1·8	3·1	3·2
8	3·0	3·2	0·4	0·1	3·4	3·3	3·9
9	2·6	2·8	0·4	1·1	3·0	3·9	3·6
10	5·1	4·6	1·4	1·1	6·5	5·7	5·3
11	3·3	3·6	1·5	0·8	4·8	4·4	4·2
12	1·5	2·8	0·6	0·5	2·1	3·3	3·3
13	2·7	2·8	0·9	0·1	3·6	2·9	3·3
14	6·1	6·2	1·5	1·0	7·6	7·2	6·9
15	3·0	4·4	1·8	0·4	4·8	4·8	5·0
16	1·8	3·0	1·3	0·7	3·1	3·7	3·7
18	1·6	2·0	0·5	0·7	2·1	2·7	2·9
20	3·2	2·7	4·5	0·7	7·7	3·4	3·3
21	2·5	3·0	0·5	0·1	3·0	3·1	3·6
22	3·3	4·1	1·4	1·1	4·7	5·2	4·7
23	3·1	3·6	0·5	0·5	3·6	4·1	4·2
24	2·0	2·5	0·1	0·4	2·1	2·9	3·1
25	1·2	3·0	0·8	0·4	2·0	3·4	3·5
26	3·1	4·0	1·7	1·2	4·8	5·2	4·6
27	1·3	1·3	2·9	1·2	4·2	2·5	2·2
28	2·7	2·5	2·0	0·0	4·7	2·5	3·1
29	2·6	1·6	0·8	0·8	3·4	2·4	2·4
30	6·9	5·7	0·9	1·2	7·8	6·9	6·3
31	3·8	2·8	1·6	1·7	5·4	4·5	3·4
32	3·7	3·0	2·0	1·1	5·7	4·1	3·3
33	3·4	3·1	2·3	1·2	5·7	4·3	3·8
34	2·1	2·1	1·2	1·1	3·3	3·2	2·8
35	2·5	2·4	1·5	0·4	4·0	2·8	3·2
36	4·5	2·5	1·2	0·0	5·7	2·5	2·9
37	2·3	1·1	1·3	0·8	3·6	1·9	1·8
38	3·9	3·8	2·0	1·2	5·9	5·0	4·6
39	3·5	2·8	1·1	0·4	4·6	3·2	3·5
40	4·6	4·1	0·7	0·4	5·3	4·5	4·7
41	3·5	2·0	4·0	1·5	7·5	3·5	2·8
42	4·3	3·2	0·9	0·5	5·2	3·7	3·9
43	4·0	2·7	1·5	0·3	5·5	3·0	3·2
44	5·0	3·3	0·4	0·6	5·4	3·9	3·8
45	5·9	5·6	0·2	0·3	6·1	5·9	6·1
46	3·6	2·9	0·8	0·6	4·4	3·5	3·4
47	3·5	3·2	0·8	0·2	4·3	3·4	4·0
48	4·2	2·2	0·1	0·3	4·3	2·5	2·5
49	2·7	1·8	0·3	0·4	3·0	2·2	2·0
50	2·9	2·4	0·6	0·1	3·5	2·5	2·9
51	2·4	2·7	0·8	0·0	3·2	2·7	3·2
52	3·0	2·3	4·2	0·7	7·2	3·0	2·6
53	3·1	2·8	7·1	1·8	10·2	4·6	3·5

APPENDIX 5 (A)—*continued*

Plot No.	B.A. Growth ex. Ingrowth		B.A. Ingrowth		B.A. Growth including Ingrowth		
	Actual	Predicted	Actual	Predicted	Actual	Predicted by addtn.	Predicted by eqn. (5)
54	2·3	2·3	3·7	0·1	6·0	2·4	2·8
55	3·5	2·7	1·3	0·0	4·8	2·7	3·2
56	2·7	2·7	0·9	0·6	3·6	3·3	3·3
57	—0·3	3·1	0·1	0·1	—0·2	3·2	3·7
58	2·2	2·8	0·3	0·3	2·5	3·1	3·2
59	0·5	1·0	2·5	1·4	3·0	2·4	1·4
60	2·8	2·2	1·2	0·0	4·0	2·2	2·4
61	0·4	1·7	0·9	0·0	1·3	1·7	2·0
62	0·2	1·6	1·1	0·1	1·3	1·7	1·8

APPENDIX 5

ACTUAL AND PREDICTED GROWTH RATES BY PLOTS (1960-64)

B. Volume growth in super feet Hoppus/acre/year.

Plot No.	Volume Growth ex Ingrowth		Volume Growth including Ingrowth			Useful Volume Growth	
	Actual	Predicted	Actual	Predicted by eqn (7)	Predicted by eqn (8)	Actual	Predicted
1	452	530	472	575	542	470	504
2	334	346	334	369	369	313	343
3	220	368	240	381	380	284	353
4	496	563	585	559	580	632	540
5	631	858	633	932	871	804	809
6	809	553	825	512	561	808	522
7	617	661	673	712	672	652	625
8	692	551	702	691	566	618	526
9	481	435	501	471	455	428	423
10	1,016	605	1,046	641	620	962	576
11	811	627	864	702	641	836	596
12	451	588	466	682	600	484	558
13	702	684	727	787	695	834	646
14	1,823	745	1,850	733	760	1,780	706
15	796	837	861	949	849	1,072	789
16	392	557	417	634	572	500	532
18	401	428	420	508	451	482	419
20	715	608	889	649	622	850	578
21	706	761	718	877	774	678	720
22	877	581	908	654	595	886	553
23	781	723	790	899	735	786	683
24	530	656	530	609	668	526	621
25	465	784	478	850	794	540	738
26	704	562	737	632	576	662	535
27	285	347	406	303	370	365	344
28	795	703	864	824	715	816	665
29	476	433	496	394	453	297	421
30	1,510	1,007	1,537	869	1,015	1,482	944
31	659	530	705	418	546	622	508
32	758	419	820	405	425	788	395
33	678	570	773	538	585	750	544
34	517	483	540	476	499	500	464
35	695	528	744	654	548	678	509
36	1,021	533	1,070	597	542	776	505
37	99	196	136	177	213	286	198
38	695	488	768	513	509	585	473
39	839	660	861	753	675	986	627
40	1,053	1,044	1,070	968	1,053	1,010	978
41	405	357	569	329	379	634	352
42	1,202	940	1,221	938	952	1,260	884
43	1,006	753	1,057	793	763	1,100	708
44	1,323	849	1,326	894	858	1,300	797
45	1,762	1,897	1,764	1,549	1,895	1,778	1,760
46	662	384	675	401	394	525	366
47	574	528	621	599	544	125	505
48	834	481	834	502	484	846	450
49	544	431	548	382	435	676	404
50	723	673	733	719	683	690	635
51	687	674	712	784	686	682	637
52	635	449	830	454	454	700	422
53	480	364	762	315	384	632	357

APPENDIX 5 (B)—*continued*

Plot No.	Volume Growth ex Ingrowth		Volume Growth including Ingrowth			Useful Volume Growth	
	Actual	Predicted	Actual	Predicted by eqn (7)	Predicted by eqn (8)	Actual	Predicted
54	523	607	680	587	618	616	574
55	734	632	774	763	644	684	598
56	688	563	714	636	576	632	535
57	—31	735	—28	879	746	—15	693
58	246	366	253	424	376	370	349
59	39	221	102	129	233	86	216
60	624	575	662	633	577	622	536
61	102	448	119	450	453	102	421
62	42	335	75	271	340	39	316

APPENDIX 6

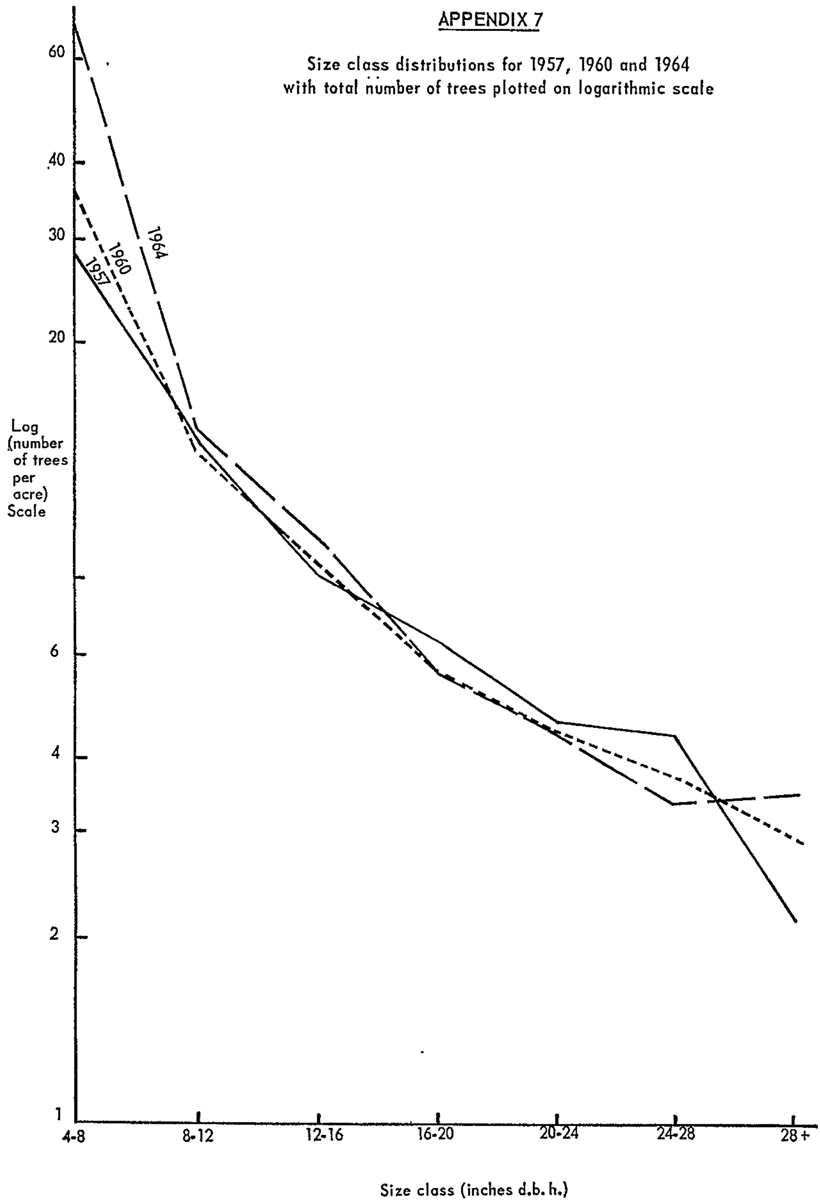
STAND-TABLE PROJECTIONS

(after Husch)

D.b.h. class	Present stand-table (1960)	4½ Yr. d.b.h. incrt.	M ratio	No. of trees moving up *n* classes		Future stand-table (1964)	Volume per tree	Future stock table (1964)
				0	1			
Using CFI Growth Data								
Ingrth	..	..	..	..	..	22·7	} 9	392
4-8	35·5	1·62	041	20·9	14·6	20·9		
8-12	13·3	1·12	028	9·6	3·7	24·2	78	1,888
12-16	8·4	1·17	029	6·0	2·4	9·7	199	1,930
16-20	5·7	1·12	028	4·1	1·6	6·5	404	2,626
20-24	4·5	1·26	032	3·1	1·4	4·7	658	3,093
24-28	3·8	1·40	035	2·5	1·3	3·9	954	3,721
28 + ...	3·0	2·07	052	1·4	1·6	4·3	1,417	6,093
								19,743
Using Management Plan Growth Data								
Ingrth	..	..	..	..	..	22·7	} 9	380
4-8	35·5	1·80	045	19·5	16·0	19·5		
8-12	13·3	1·80	045	7·3	6·0	23·3	78	1,817
12-16	8·4	1·35	034	5·4	2·8	11·4	199	2,269
16-20	5·7	1·35	034	3·8	1·9	6·6	404	2,666
20-24	4·5	1·35	034	2·9	1·5	4·8	658	3,158
24-28	3·8	1·35	034	2·5	1·3	4·0	954	3,816
28 + ...	3·0	1·35	034	2·0	1·0	4·3	1,417	6,093
								20,199

APPENDIX 7

Size class distributions for 1957, 1960 and 1964
with total number of trees plotted on logarithmic scale



APPENDIX 8

COMMENTS ON SOME OF THE INDEPENDENT VARIABLES ORIGINALLY TESTED

The following notes may help to elucidate some of the variables used in the first screening of independent variables.

1. *Mean dominance class.* Each tree on the plots was classified as either a Dominant (coded as 1), a Co-dominant (2), a Sub-dominant (3), or a Suppressed (4), tree. Since dominants and co-dominants have been shown to grow faster than the other stems, it was considered a possibility that some plots may have proportionately more dominants and co-dominants than others and thus may grow faster. This was quantified by summing all the dominance codings and dividing by the number of trees, giving a mean dominance class.

2. *Mean crown class.* Similarly each tree was classified as having a Good (1), Medium (2), or Poor (3), crown. This was quantified in a similar fashion to mean dominance class, the assumption being made that it was possible, for instance, that plots having all good crowns (mean crown class = 1·0) might have significantly better growth than those having all poor crowns (mean crown class = 3·0).

3. *Soil type.* In 1957 the soils on each plot were descriptively classified on such characteristics as depth, colour, and texture. Arbitrarily it was decided to divide these into four groups. Group 1 included those soils described as rich, deep, good, red, alluvial, etc. Group 2 included soils described as red-brown, brown, medium, etc. Group 3 had soils described as yellow-brown, yellow, etc. Group 4 soils were described as yellow-grey, grey, glei, stony, gravelly, shallow, etc. These were entered as three dummy variables in the regression screen, e.g., Group 2 was coded 010.

4. *Aspect.* This was coded from 1 to 8, ranked roughly according to the amount of solar radiation received, the southerly slopes receiving the least. The coding used was:—

SE	1	NE	5
S	2	W	6
E	3	N	7
SW	4	NW	8

5. *Slope.* The actual slope in degrees as measured by Abney level, was used as the code.

APPENDIX 9

ADDITIONAL VARIANCE EXPLAINED BY REJECTED INDEPENDENT VARIABLES

Due to the fact that the rejection of inconsequential variables occurred in the early stages of this rescarch, when the computer programmes were still being tested, it was impractical to test all the independent variables simultaneously for each equation. Indeed the restrictions of the programmes made this impossible.

In addition, there is a considerable saving in computer time if the assumption is made that usually about three or four variables in regression equations of this nature account for most of the variation.

Further, it was assumed that variables which accounted for little of the variation in the basal area growth equations would account for little in the volume growth equations.

The most complete list of independent variables available is therefore for the screening of basal area growth excluding ingrowth (with four soil groups). In this screening, the results indicated that number of trees per acre and percentage of blackbutt by basal area were the best two variables, accounting for 71·2 per cent of the total variation. The following list gives the additional percentage of variation accounted for by the corresponding variable when taken as a third independent variable.

	Per cent
Basal area/acre	0·1
Sum of diameters/acre	0·3
Mean merchantable height	1·8
Sum of diameters/ acre × mean merchantable height	0·6
Mean diameter	0·3
Standard deviation of diameters	0·3
Coefficient of variation of diameters	0·1
Mean basal area per tree	1·7
Percentage blackbutt by number of trees	0·5
Mean dominance class	1·0
Percentage dominants and co-dominants by number	1·0
Percentage dominants and co-dominants by basal area	0·4
Mean crown class	0·1
Soil type	4·6
Aspect	1·0
Slope	3·0

The best of these is Soil type. In fact these three were the only statistically significant variables. Subsequent screening of volume growth substantiated the assumption that variables rejected in the basal area screening could also be rejected in the volume growth analyses.

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