THE PREDICTION OF GROWTH AND WOOD QUALITY PARAMETERS FOR PLANTATION GROWN *PINUS RADIATA* D. DON. IN NEW ZEALAND

by

R. N. JAMES
St. John's College



A thesis submitted for the degree of Doctor of Philosophy at Oxford University.

Trinity Term, 1983.

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This work develops parameters which link silviculture to the two most important intrinsic properties, wood density and tracheid length. Both of these properties vary more or less regularly with geographic region. Within individual trees values depend on wood-age (= rings from pith). The properties of a stand of trees can be assessed if volume per tree can be partitioned into wood age categories. The parameter suggested here as best indicating wood quality whilst also having relevance to silviculture is volume of mature-wood, that is volume of wood age greater than ten years.

A replicated spacing/thinning trial of 75, 0.06ha plots provided the data source. Models were developed to predict the wood quality parameter. Diameter growth is projected for a plot by means of an individual tree, distance dependent model based on multiple linear equations. Height is predicted from age and diameter by a system of homologous non-linear equations and volume per tree by a function of diameter squared and height. From diameter, height and age, mean wood age is predicted using a multiple linear equation and the distribution of volume by wood age is predicted using the Weibull function. The distribution is applied to each tree and totalled for the stand.

Comparing results at a fixed age for a wide range of silvicultural regimes reveals that silviculture has a greater influence on wood quality than hitherto believed.

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CHAPTER ONE

INTRODUCTION

1.1 Background to N.Z. Plantation Forestry

The history of forestry in New Zealand and in particular the development of modern plantation silviculture has already been given in a number of papers, for example Fenton and others (1972), Sutton (1976) and Sutton (1978). A brief outline will however be repeated here to demonstrate the relevance of the current research, quoting mainly from these accounts.

New Zealand was once mainly covered in native forest, today this has been reduced to about 20% of land area (under all forest classes including unproductive forest). The forest that existed before European settlement was felled only partly in order to obtain timber, much was cleared for subsequent development as pastoral farmland. This indigenous forest is usually classified as sub-tropical; the trees are relatively slow growing and the forest eco-systems 'fragile' and not suitable for the application of modern silvicultural techniques. This was recognised by a Royal Commission set up in 1913 to review forest production and estimate future demand for forest products. The Commission recommended a large-scale afforestation programme using exotic species to satisfy the expected future domestic demand for timber products. To implement these findings, the State Forest Service was formed in 1919 under a Canadian, MacIntosh Ellis. In his policy reviews of 1920 and 1925, Ellis estimated that 125,000 hectares of plantation were needed. By 1931 this target had been achieved with about half in State and half in private ownership, and mostly located in the central North Island plateau about

the towns of Tokoroa, Rotorua and Taupo. Today 90% of forest production comes from exotic plantation forests.

Radiata pine (Pinus radiata D.DON) a native of the Monterey Peninsula of California was first planted in New Zealand about 1850 (Weston 1957) and the value of the species was recognised by the 1913 Royal Commission which described it as capable of yielding 'a really good second-class timber when from thirty to thirty-five years old'. This was a perceptive assessment and the theme of quality and its relationship to the age of the tree constitutes one of the major themes of the present work. The major part of these early plantings was of radiata pine, overwhelmingly so in forests in private ownership.

The resource established during the late 1920s and early 1930s is usually referred to in New Zealand as the 'old crop'. For a variety of reasons including a lack of markets for small-wood and shortage of labour during the second world war, the old crop received virtually no silvicultural treatment. Even after the war, because of a reluctance 'to thin their own handiwork with any severity' there was not much thinning done on a management scale and because of a 'deplorable lack of the spirit of enquiry' there was no real attempt at experimental silviculture (Hinds 1962).

By the late 1940s the stands of old crop were considerably overstocked and many of the smaller trees had died from competition induced mortality; at this point there was an epidemic of the sirex wood wasp (Sirex noctilio F) which resulted in a 'natural' thinning varying in severity from stand to stand. Since 'losses were usually confined to small lower dominance trees and growth was concentrated onto fewer stems' (Sutton 1976), the net effect of this epidemic is regarded as positive. This is the brief history of a resource, the last of which is still being utilised, that

has for more than 30 years supplied wood for New Zealand's home and export needs; for sawn timber as well as products based on chemical and mechanical pulps and for round-wood products such as fence posts and building poles.

1.2 Evolution of Silvicultural Practice in New Zealand

The first attempts to apply a systematic regime of silvicultural treatment began in 1949, (Ure 1949) and by 1953 the early proposals had been modified to a regime that contained pruning in the butt log region to remove branches as a sawn timber defect, and two thinnings, one with, and one without, yield (Peniston 1960). Rotation age was envisaged as 40-45 years on central plateau 'pumiceland' sites. This regime and variations of it were widely practised throughout New Zealand's radiata pine plantations from around 1950 until about 1975. In 1968 an alternative schedule was proposed (Fenton and Sutton 1968) in which stands would be reduced to final crop stocking immediately after pruning and the thinning with yield dispensed with. The regime was later modified (Fenton et al., 1972), but the productive thinning was not replaced. It is this regime (and its local variations) which dominates New Zealand silviculture today. The rationale for the new regime (called the Direct Regime) is fully given in the papers referenced and will not be repeated here. It is relevant, however, to mention that these reasons covered the fields of forest operations, wood quality and economics and that partly in response to economic constraints, the rotation length was reduced from 40+ years to about 25 years. Wood quality would be greatly improved in the butt log region by the removal of defect causing branch wood (i.e. by the operation of pruning off all branches in the butt region); but there remained serious doubts about deterioration in intrinsic properties in wood harvested from such a regime.

1.3 Wood Quality and Export Potential

These doubts cannot be dismissed lightly. New Zealand has placed considerable emphasis on diversification away from its traditional sources of foreign exchange earnings; farm products: wool, sheepmeat and butter. Part of that diversification has been investment in forestry. Following the first National Forestry Planning Model in 1969 the rate of new planting increased to 18,000ha/annum, by the mid-1970s this had more than doubled to 40,000ha per year; nearly all in radiata pine. The current plantation area stands at about 900,000ha. The majority of these stands will be managed on the 'direct regime' with its shortened rotation. This reduction in clearfelling age has been documented by Levack (1979) who in a report on the 1977 National Forestry Planning Model noted a steady and inevitable decline in rotation age from 48 years in 1980 to 29 years by 1996. (These figures are national averages and many stands will be felled at a younger age.) Since all of this increased forest estate is designed to provide products for export, not for internal demand, (Hosking 1972), quality must be an important selling point. The case for manipulating the forest resource to produce wood products of high quality has been already argued by Sutton (1978). In an analysis of world forestry resources, international trade and the possibilities of tailoring the New Zealand resource to supply a specific type of product, he argues for regimes of the 'direct' type to supply 'clear' (i.e. knot free) sawn timber; arguing that this, rather than products based on pulpwood or sawn timber with knots, will be the type of product most scarce in world markets and for which New Zealand has a comparative advantage. Although Sutton equated quality with the absence of knots, the logic of his case (in which the current author entirely concurs) depends on the production of wood that is of high quality in other respects also. That is, the regime which produces

the long clear lengths favoured for the export market must not, at the same time, result in the down grading of other properties intrinsic to the wood which might either detract from or override the designed increase in quality. Although it was argued that 'clear' sawn timber was the most desirable product, it was also noted that pulpwood is an invariable by-product of sawlog regimes and that an export trade in pulp products already exists for New Zealand, and will almost certainly continue. For such products, intrinsic wood properties are of great importance. Developing a methodology for predicting the relationship between silviculture and tree growth and between tree growth and intrinsic wood properties will form the subject of this thesis.

CHAPTER TWO

THE IMPORTANCE OF INTRINSIC WOOD PROPERTIES

Formal warning of a deterioration in wood quality with shortening of rotation was given by Harris et al. (1976). Reporting results from a pilot sawing study and of theoretical calculations of strength and stiffness effects, they noted that a fall in basic wood density was accompanied by a fall in stiffness and strength. They stated that an increase in wood density could compensate for the increased knot size they expected from the widespread application of the direct regime and argued that this could be achieved by tree breeding. The relationship between strength and basic wood density was recently confirmed by Whiteside (1982) who repeated the sawing study on a full scale basis. He found that for sawn timber, strength, stiffness and surface hardness can all be related to basic density.

For wood pulps and the papers made from them the picture is more complex. The character of wood pulp depends both on the pulping process and on subsequent treatment aimed at modifying the intrinsic properties of the primary pulp. For Kraft pulps the process is a chemical one and preserves the fibre more or less intact. Such pulps make papers with high tear strength and are either used where this property is highly desirable (e.g. for wrapping paper) or as an additive to boost the strength of other pulps. The actual strength of such papers is related to the dimensions of the fibres and to wood density. This is well established, for example, Kibblewhite (1980) found handsheet tear strength for radiata pine Kraft pulps beaten for 2,000 revolutions to be clearly related to wood-chip density (r^2 = 0.789) or; in a similar test, when tear strength was measured for pulps stabilised at a burst strength of 7.5kPam^2/g, to be clearly related to fibre length (r^2 = 0.74).

Intrinsic properties are less critical for mechanical or thermo-mechanical pulps. Such pulps, by the nature of the pulping process, will be composed of fibres that have been modified thus obscuring the effect of their original properties. However, Bunn (1981) says that 'experience in New Zealand is that higher density wood gives superior pulp' while noting that good quality refiner pulps have also been made from wood of low density. He also notes that there are speciality papers for which thin walled fibres (from low density wood) are preferred. These fibres result in a more compact, denser sheet with improved printability. Bunn (1981) summarizes by foreseeing 'a trend towards more "scientific" papermaking' for all processes, with more detailed segregation of fibre types according to the paper properties desired.

With the pursuit of quality an issue of great importance to New Zealand's forest products industries and the effect on paper quality of intrinsic wood properties such as basic density and fibre length clearly established, a method of relating intrinsic properties to forest conditions would clearly be advantageous.

CHAPTER THREE

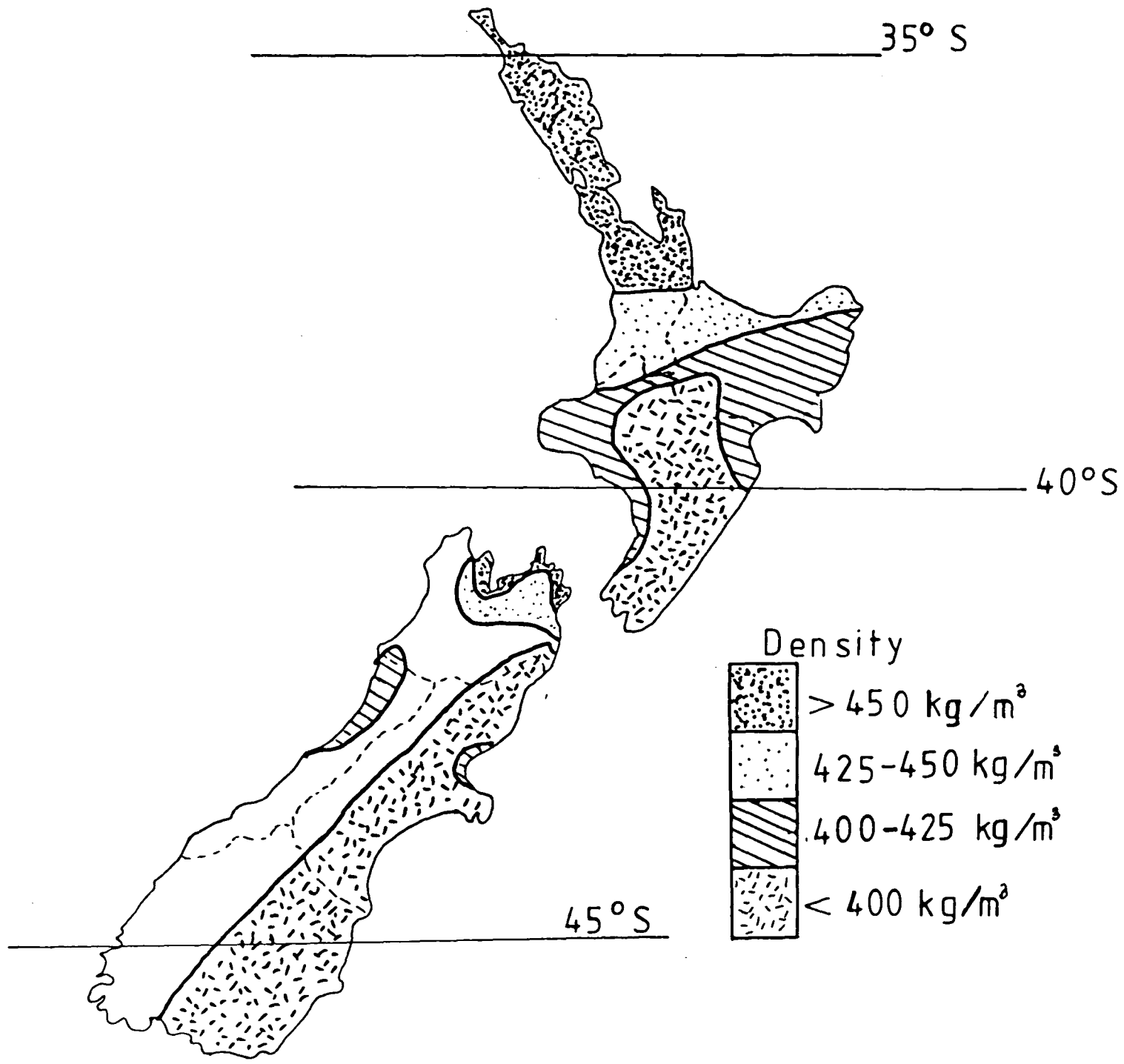
SILVICULTURAL PARAMETERS WHICH REFLECT INTRINSIC WOOD PROPERTIES

3.1 Variation in Intrinsic Properties

Although intrinsic wood properties such as chemical composition and the amounts of compression wood, extractives and heartwood are all important in the utilisation of radiata pine, the two most important properties are wood density and fibre (i.e. tracheid) length. The property 'basic wood density' is important not only in that it is related to external characteristics with high market value (such as timber strength or paper tear strength) but because it 'summarizes' the combined effect of such intrinsic properties as cell diameter, cell wall thickness and percentage latewood.

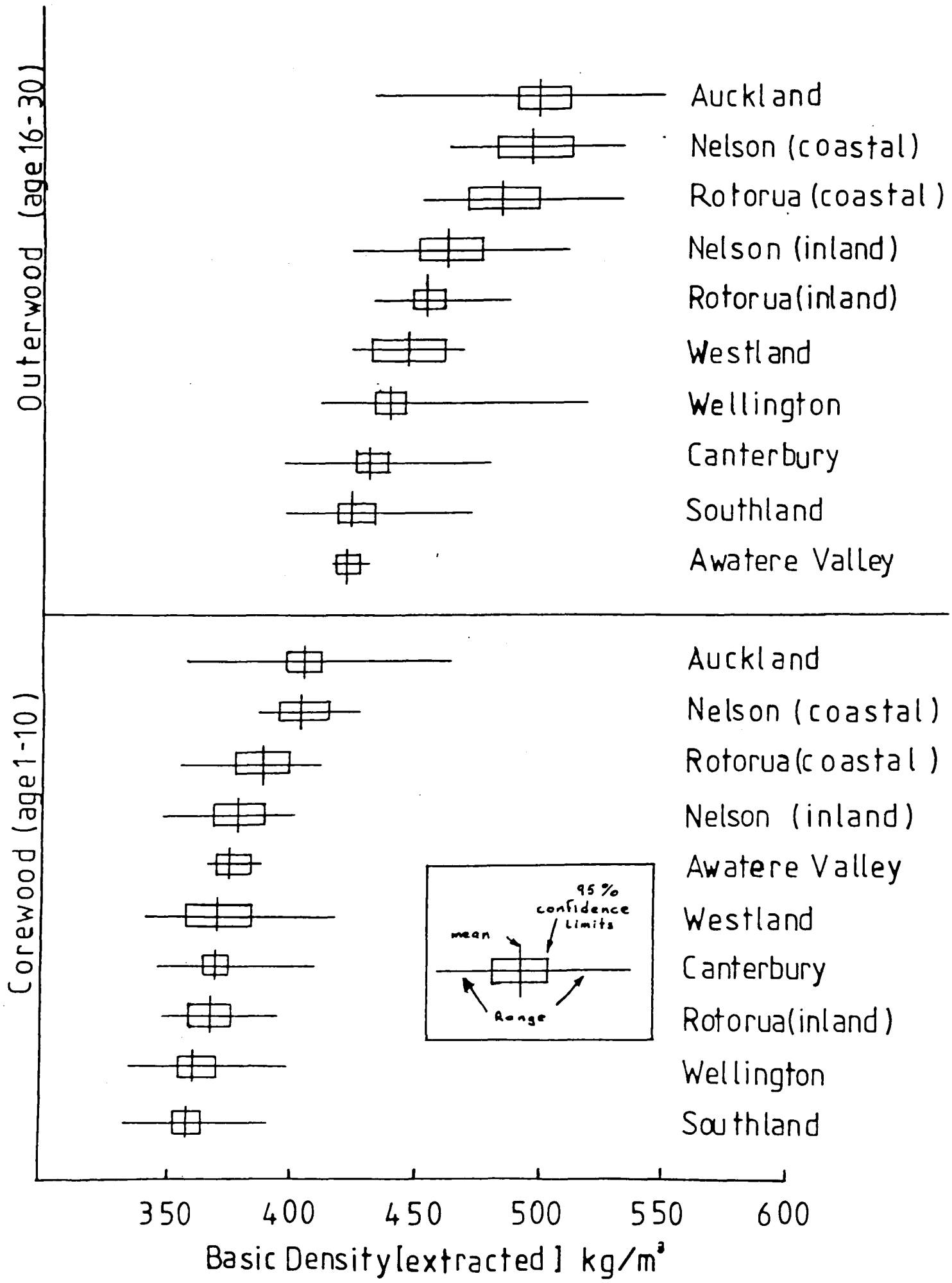
For ratiata pine grown in New Zealand wood density is subject to three sources of variation; between geographic regions, within stands, and within trees. Fortunately regional variation is systematic and can be quantified. Harris (1965) reported results from a regional survey of wood density. He examined increment cores from 2,800 trees growing on 37 sites and found a high correlation between density and mean average temperature, (r^2 = 0.88). More recently Cown and Kibblewhite (1980) have reported on another nationwide survey of 235 sites. They confirm the observations of Harris and have been able to define quite precise climatic/density zones by geographic region. These regions are shown in Figure 3.1, and the range of values and 95% confidence limits of the estimate of the mean value of corewood and outerwood density for each region are shown in Figure 3.2. For the regions with the greatest variation (Rotorua coastal and Westland) the 95% limits are equivalent to a deviation of $\pm 15 Kg/m^3$ from the mean.

Figure 3.1 Geographical Distribution of Radiata Pine Density Classes in New Zealand



[after Cown &Kibblewhite, 1980]

Figure 3.2 Corewood and Outerwood Density Values - By Region



[after Cown & Kibblewhite, 1980]

Within-stand variation in density has not often been described. Cown and McConchie (1980) report on the examination of ten trees in an old crop stand aged 52 years. Their sample was chosen to include extreme values and for a sample mean whole treee basic density of 420Kg/m^3 they found minimum and maximum values of 370 and 461Kg/m^3. No comparable data are available for the new crop.

In this investigation results of silviculture parameters which are related to intrinsic wood properties are given at stand level.

Both regional and stand values of wood density may in future be increased by tree breeding. As noted by Harris et al. (1976), density is one of the most heritable of all the commonly considered characteristics of radiata pine. Moreover, it exhibits no genotype environmental interaction so that selection for wood density made on one site will apply elsewhere.

Of greatest relevance to the present work, however, is the variation within each tree. Harris (1965) in the results of the first national survey, noted a steady increase in density from core to outer wood.

Uprichard (1971) in a systematic examination of within-tree variation for five sample trees also noted a consistent increase in density towards the outer wood and commented that this rise was most rapid over the first 10 to 15 growth rings from the pith. Later in Harris et al. (1976) it was stated that this increase 'is almost linear up to 25 to 30 growth layers from the pith ... so that trees felled at 25 years are only just beginning to produce wood of maximum density'. The pattern of density change with age in radiata pine is well established and completely accepted. Similar patterns are found in other softwoods but for radiata pine this pattern is little altered by growth rate. This point has been made in general comments such as in Harris (1965) - 'it is clear that variation

between trees is such that rate of growth cannot be regarded as playing a major role in determining specific gravity'. It has also twice been specifically investigated by comparing wood from trees of the same age but which had received different thinning treatments. Cown (1974) compared 25 year old trees and found some differences in density in wood up to 6.1m high but the differences are small and significant at the 10% level only. When measured by radial densiometer, Cown noted that the familiar trend of increasing density was abruptly halted in the rings following thinning at both thinning levels investigated. His illustrations show that normal trends, (with considerable annual fluctuation), resumed shortly afterwards. In the second case, Sutton and Harris (1973) investigated 16 year old trees from a stand where a small area had fortuitously been over-thinned. They also used the beta-ray radial densiometer to investigate density changes. They noted considerable increase in ring width following the thinning but, when smoothed to take account of considerable annual fluctuation, there was no change in wood density.

Whiteside (1982) found that mean ring width was not a significant variable when predicting either value or percentage out-turn of machine graded timber from individual logs when using multiple regression analysis. In Harris et al. (1976), it was stated 'rapid radial growth rate has a very small depressant effect on wood density within normal limits of growth ... thinning, therefore has little direct effect on wood density when considered over the length of the rotation. By far the most important differences in intrinsic wood properties arise from the relative proportions of corewood and outerwood formed under different regimes.' This point is not only important to the logic of this study, it is important for international trade. In 1981 the Japanese government lifted the ring width restriction which had proscribed radiata pine for use as a

construction timber in Japan. They have replaced it with a restriction on the occurrence of pith and corewood (NZFS 1981) thus giving formal recognition to the role of intrinsic properties in determining timber strength and conceding that for radiata pine rapid growth does not indicate significantly diminished strength.

In the case of fibre length, the pattern is less clear. Harris (1965) found that correlations between tracheid length and annual temperature or altitude were less pronounced than for wood density, (r^2 = 0.56 and 0.59 respectively). Nevertheless, a regional pattern exists on a similar but less clearly defined basis than the pattern for density (Cown and Kibblewhite 1980). For example, the Auckland region which has the highest wood density also has the longest tracheids.

Within-tree variation in tracheid length also follows a similar pattern to wood density with tracheid length increasing with wood age. This is clearly shown by Uprichard (1971) where values for five sample trees are shown by rings from pith or wood age. Maximum values for each tree, however, did not occur with the oldest wood. Cown (1980) also notes this pattern and states that the longest fibres will be produced 'at about half stem height'. In spite of this difference, when discussing the effect of wood age on intrinsic properties, Uprichard (1980) treats wood density and tracheid length together when relating wood age to wood properties. The pattern of change in values with change in wood age is regarded here as essentially identical for these two intrinsic properties. (Other properties such as moisture content, heartwood and extractives content do not vary in the same way.)

3.2 Silvicultural Parameters

With the pattern of within tree changes in density and tracheid length well established, the problem becomes one of relating this to parameters that also have meaning for the silviculturist. Uprichard (1971) in his study of within-tree variation of properties, gave details of density and tracheid length variation from pith to outerwood at different heights up the stem. When presented as 'rings from pith' the values agreed closely regardless of height. It is not clear who first stated that wood formed at a given number of rings from the pith will have much the same basic density and fibre length no matter at what height the wood was formed, but this is now accepted. The terms 'physiological age', 'cambial age' or simply 'wood age' have been used to describe wood of the same age and properties (Balodis 1966, Grant 1978, Uprichard 1980), the simplest term, wood age, will be used here. Once the concept of wood age became established, interpretation of changes in pulp and timber quality with position in the stem or age of the tree became more straightforward. For example, quoting from Uprichard (1980)

> Variation in wood properties with tree age is a most important concept in pulpwood utilisation and often receives less attention than it deserves ... samples formed at the same number of growth rings from the pith have been produced at the same formation stage of tree growth and may therefore be considered to have approximately the same wood age ... tear strength is the papermaking property most influenced by wood age and therefore the parameter of most concern when considering the changes in forest age on the quality of Kraft pulp available for export.

It is thus clearly established that within each tree, the two most important wood properties vary with wood age. The converse is also true, if wood age is given, wood properties can be estimated. Since this is true for all ages of wood, the properties of whole trees can be estimated if the volume of wood within those trees could be broken down by wood age.

Table 3.1. Variations in properties with wood age

Property	Rings from Pith 1-5	6-10	11-15	16-25	26-30
Wood density Kg/m^3	357	401	413	453	491
Fibre length (mm)	2.9	3.7	3.7	4.1	-
Kraft Pulp beaten 4000 rev.					
Tear Index	12	19	29	29	39
Burst Index	7.0	6.8	5.5	5.4	4.8

From Uprichard (1980), example is from a tree of high density

This provides the link between wood technology and silviculture because it is the stock-in-trade of the silviculturist to estimate growth rates and volumes for stands where he has prescribed the treatment schedule. To provide the information necessary for the estimation of intrinsic wood quality it is necessary to estimate the volume yield sub-divided into wood-age categories.

The final link between wood-age and actual values of intrinsic properties such as basic wood density will not be made in this work. It has, however, been demonstrated that these links are possible to construct with the appropriate knowledge of wood quality.

CHAPTER FOUR

EARLIER ATTEMPTS TO FORECAST WOODAGE EFFECTS

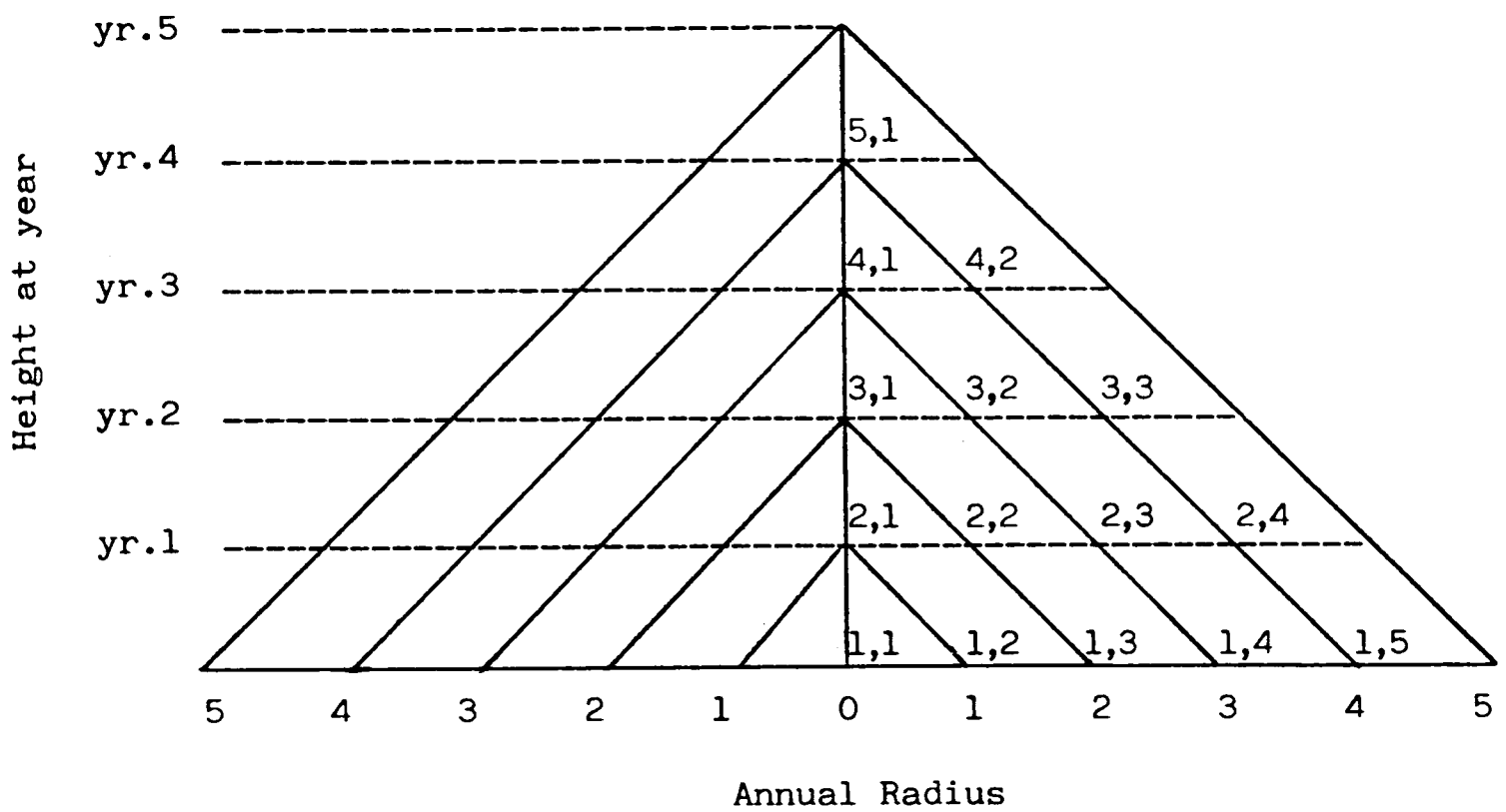
The concern within New Zealand forest management with the effect of reduced rotation age has already been referred to. This is still seen as an unresolved problem because while it is acknowledged that shortening the rotation will affect fundamental properties, the extent of the change is not known. For example, when reviewing the nature of New Zealand's future plantation resource, Bunn (1981) said

> Rotation age has become a vital factor in many regions and in this situation it is essential that we understand how stand age, location, site index, stocking and pruning interact to influence wood properties, treecharacteristics and value outturn for different products if we are to succeed in channelling logs to their most appropriate end use.

To some extent the effect of earlier felling can be approximated by sampling only the upper stem of older trees. This was done by Uprichard (1980) and effectively illustrates the type of change that occurs. It cannot be used to provide more detailed estimates however, because the proportions, by volume, of wood of each wood-age may not be the same for the upper section of a tree as it would have been if that section had been based at ground level.

This was recognised by Grant (1978) who constructed a model for predicting the impact of silviculture on wood characteristics. He took the well known layered pattern of tree growth where for purposes of illustration each year's growth can be visualised as a hollow cone fitted over the solid cone of the preceding year's growth. Such a model is shown in Figure 4.1 (reduced to two dimensions).

Figure 4.1. Schematic Representation of Tree/Wood Age Model



After Grant 1978.

The notation used is that of Balodis (1966). The volume of age 0.5 wood (average of 0 to 1 year) is the sum of the cones (1,1) + (2,1) + (3,1) + (4,1) + (5,1); of age 2.5 wood the sum of the sections (1,3) + (2,3) + (3,3). In developing and testing his model, Grant chose regimes where the tree of mean diameter could be expected to represent the tree of mean volume growth and mean wood properties. He suggested that silvicultural regimes such as the 'direct regime' would fulfil this requirement, but specifically excluded heavily stocked stands from the model he tested. Grant's model takes the diameter and height of the mean tree for a given year, uses Gray's Taper Line (Gray 1956) to derive intermediate annual diameters and calculates the 'mean physiological age' of the tree. He was able to obtain data derived from stem analysis for 47 trees from two thinned sample plots against which to test his model. The results of these tests

showed that it was possible to model the change in mean wood age, at least for regimes where the growth on every tree was continuous and even.

CHAPTER FIVE

PREDICTION OF WOOD QUALITY PARAMETERS: AN OUTLINE OF THE METHOD USED

While most of the concern about changes in wood quality has been expressed in terms of rotation length, Grant's analysis highlights the point that it is the whole effect of the silvicultural regime that has to be considered when estimating changes in wood age. Earlier it was stated (Harris et al. 1976), that

> Mensurational data necessary to determine precisely the different mean wood densities resulting from different silvicultural regimes are not yet available. To derive these figures accurately, the volumes produced down each stem in each year must be known for representative trees.

These data have now been obtained and in combination with data from an already existing series of sample plots a model system has been developed to forecast volume by woodage. This has been tested over a range of silvicultural schedules with widely varying stocking rates.

The strategy adopted for the model is to commence with details of age and diameter for each tree in a plot where the plot is a representative sample of the regime under investigation. To then predict for future years the diameter distribution of the sample stand and from the age and diameter predict height. Using diameter, age and height as the major independent variables, the mean wood-age for each tree is predicted. Then, by using a distribution function, the percentage distribution of volume about the mean is obtained for each tree. A volume table was constructed to give individual tree volumes (to a 10cm top) based on diameter and height as independent variables. By applying the percentage distribution for each tree to the individual tree volume and totalling, the yield by volume of wood in each wood-age can be obtained for the whole sample plot.

CHAPTER 6

THE DATA SOURCE

6.1 History of the Stands

The data for all aspects of this work are derived from the Tarawera Valley Regimes Trial - a replicated spacing/thinning trial located in forests owned by the Tasman Pulp & Paper Co. in the Tarawera Valley, near Kawerau, New Zealand. The author was chiefly responsible for the design of the trial and has been responsible for its installation and maintenance since 1969. The trial has already been described in outline (James 1976) but a description is repeated in detail here. The total area of trial is approximately 13.5 hectares all radiata pine, established in 1963 as part of the future wood supply to an integrated pulp/paper and sawmill complex. Because the soil type in the area was unique and untried as a forest soil (black scoria from volcanic eruption in 1866) the forest company was unsure of the best rate of initial stocking to apply and planted three contiguous blocks at 9 x 9, 6 x 6 and 4½ x 4½ feet (i.e. 2.7 x 2.7, 1.8 x 1.8 and 1.3 x 1.3 metres). These three blocks and an adjacent area planted at the company's standard spacing of 7 x 7 feet (2.1 x 2.1m) were offered to the Forest Research Institute in 1969 for research purposes.

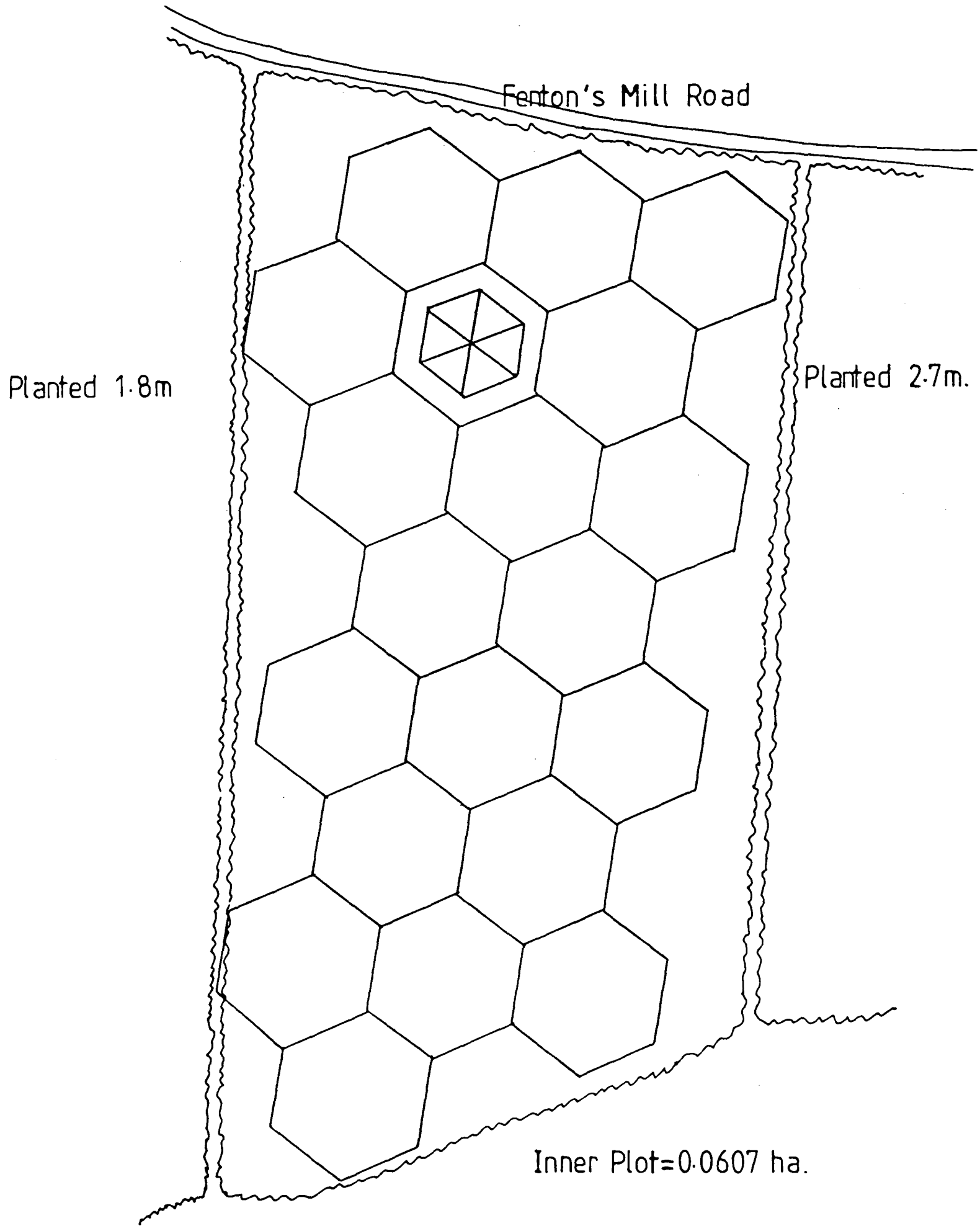
6.2 Design of the Field Trial

It was decided to use the area to compare a suite of related silvicultural regimes. The objective of the trial was to obtain the physical data necessary to evaluate, in economic terms, alternative ways of growing pulpwood and construction timber. The two products were linked in the one trial because in neither case did the trees require to be pruned. Because of specialised mill requirements, the pulpwood crop was to be

of small diameter trees and regimes for this crop involved one thinning to final crop stockings ranging from 500 to 1000 stems/ha. The critical factor in the design of the regimes to provide framing (i.e. construction) timber was assessed as being knot size and accordingly one final crop stocking was stipulated (380 stems/ha), but the timing of thinnings was varied in order to provide a range of control (by stand density) over branch development. (The silvicultural rationale of growing high quality framing timber without pruning is given in Fenton 1971.) Some plots were left at their original stockings so that for the whole trial stocking levels ranged from 5000 to 380 stems/ha with either none, one or two thinnings applied at ages from six years to 14 years. Thinnings were usually applied 'from below' favouring straight, unforked dominants or co-dominants, but some 'row' thinnings and one 'crown' thinning were used. For the row thinnings every third planted row of trees was removed and the crop trees selected from the remaining two rows, which were then also thinned. As applied in this trial, the term crown thinning means that the largest and smallest trees were all removed, the crop being selected from trees with diameters close to the stand mean value. The full range of schedules is given in Table 6.1.

Sample plots from each regime were laid out in a hexagonal fashion and although they were originally surveyed in Imperial units, were almost exactly 0.06ha in area. Each plot is surrounded by a 'buffer' 10 metres wide of 0.12ha, treated exactly the same as the inner plot, to insulate treatments from each other. All treatments are represented by three replicates. Except for those designated as unthinned controls, plots were only measured from the year of treatment. For all plots to be measured, each tree was identified and breast height marked. Measurements have been carried out every year since 1969 in winter (July in New Zealand)

Figure 6.1 Schematic Plan of Stand Planted at 1.3 m



until 1980. Thus for many of the plots there are records for 12 years continuous annual assessment.

Table 6.1. Regimes Represented in the Data

Regime	Nominal initial planting espacement (m)			
	1.3	1.8	2.1	2.7
Unthinned control	x	x	x	x
Thinned to 750/ha at approx 12.7m	x	x	x	x
Thinned to 1000/ha			x	
Thinned to 500/ha			x	
Thinned to 380/ha at 12.0m		x	x	x
Thinned to 380/ha at 16.5-20.0m		x	x	x
'Row' thinned to 380/ha at 16.5-20.0m		x	x	x
'Crown' thinned to 500/ha at 15.3m			x	
Thinned to 380/ha two steps	x	x	x	
Thinned to 1330/ha at 12.0m	x			

Diameter measurements were taken for every tree in each plot but height measurements were taken each year in only 24 plots. These were the 12 control plots (three plots in each spacing) and the three plots in each espacement that had received the heaviest and earliest thinning. The height parameter measured was Predominant Mean Height (PMH) defined as the height of the tallest tree per one hundredth of a hectare. Later for practical reasons, this definition was changed to the height of the tree of largest diameter per one hundredth hectare. It can be seen from Figure 6.1 that plots can be easily divided into six triangles, each 1/100ha in area, by line of sight triangulation. Trees for which height measurements were taken were selected, one from each 0.01ha triangle. During the application

of the thinning schedules some plots, in which a delayed thinning was being carried out, suffered windthrow. Accordingly, further delayed thinnings to 380s/ha were abandoned. The three plots in each spacing that this released were felled at two yearly intervals and the produce carefully measured. The intention was to provide actual volume data for examples of 'plant and clearfell' regimes for which the product would be either pulpwood or wood for conversion to energy. These data were used in this study to derive an individual tree volume table. At the same time as trees were felled to be scaled for volume, a smaller sample was selected for stem analysis. From this stem analysis the data for volume by woodage were derived.

The topography on which the plots are located is flat with only local undulations. The trial is compact, the four stands being contiguous and because they were originally conceived of as establishment trials, planting was thorough, survival good and stocking uniform. Site index is high, 35m (at age 20) using the equations of Burkhart and Tennant (1977). During the period of measurement, heights have increased from 12m to 32m (PMH). Records have been carefully kept and treatments applied on schedule; the trial represents very nearly the ideal in standardised field conditions.

CHAPTER 7

PREVIOUS ANALYSIS OF THE DATA

Two earlier analyses of these data have been given: (James (1976) and James (1978). Both dealt with data at plot level and were concerned with growth patterns and comparisons between levels of initial stocking and between rates of final crop stocking. This was in accordance with the original objectives of the trial. Because these provided the foundation on which subsequent analyses were based, and the more recent of the two papers is not generally available, the main points are repeated here.

> In unthinned stands initial differences in basal area are related to stocking level, but as stand competition intensifies these differences become less. It seems probable that the basal area of unthinned stands increases until a maximum value for the site is reached (fig.7.1). Thinning to a range of final crop stockings shows that for the first half of the rotation the rate of basal area increment is not affected, but the level of standing basal area is (fig.7.2).
>
> As long as thinning is carried out before stand competition has affected the crop element initial stocking has no effect on basal area growth or amount. Delayed thinning results in a reduction in basal area (for a given stocking) and temporary reduction in increment (fig.7.3). Two-step thinning, where the second step is delayed, only partly compensates for the reduction in standing basal area. Crown thinning is only partially successful in restricting stand diameter distribution to a narrow range and does not avoid the disadvantages of delayed thinning. Mechanical or row thinning has incurred the same disadvantages and compared with delayed thinnings carried out at the same time has resulted in a further reduction in standing basal area and the same post-thinning depression of increment.
>
> James (1978)

Figure 7.1 Basal Area - Unthinned Controls

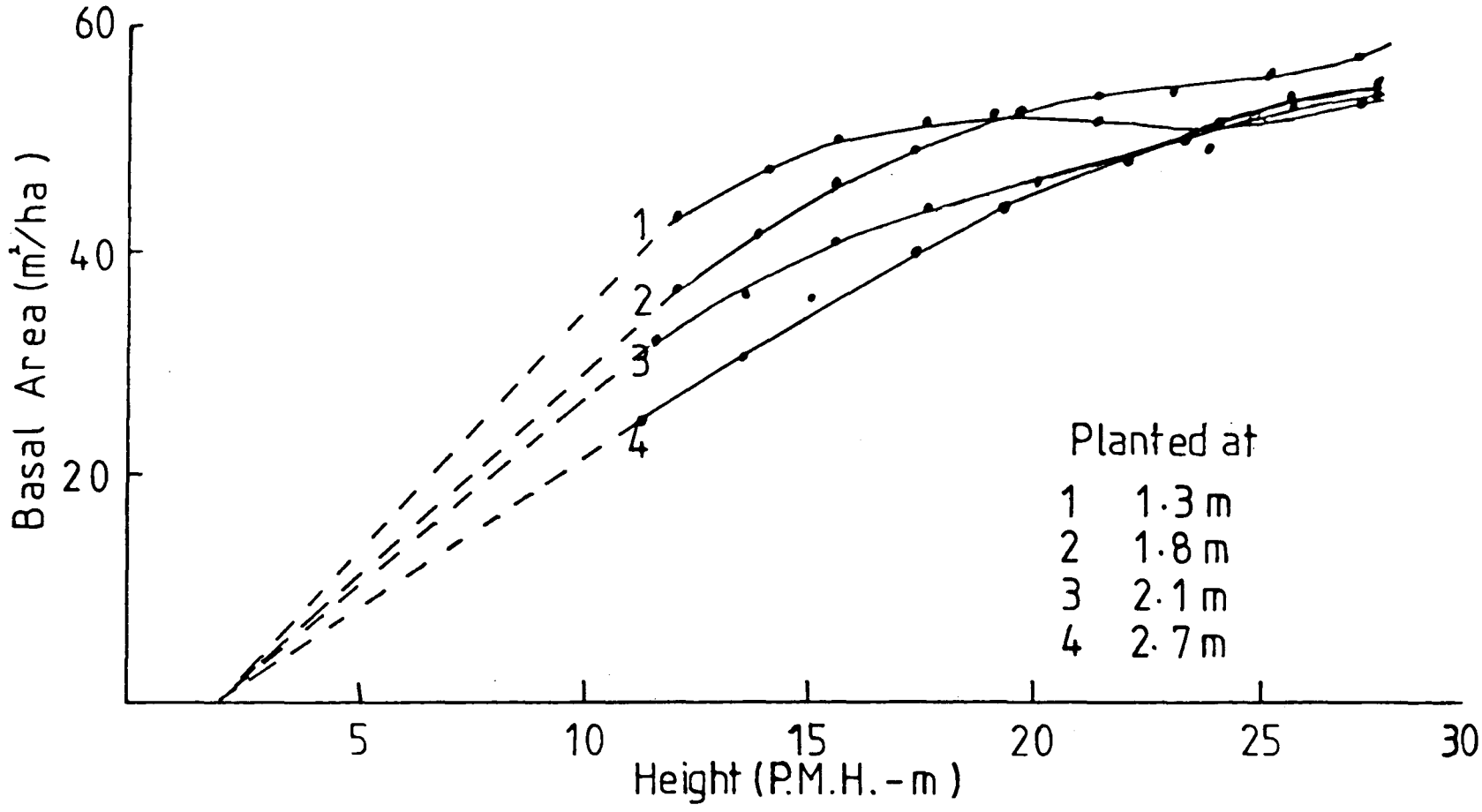


Figure 7.2 Planted 2.1m Thinned to Various Stockings

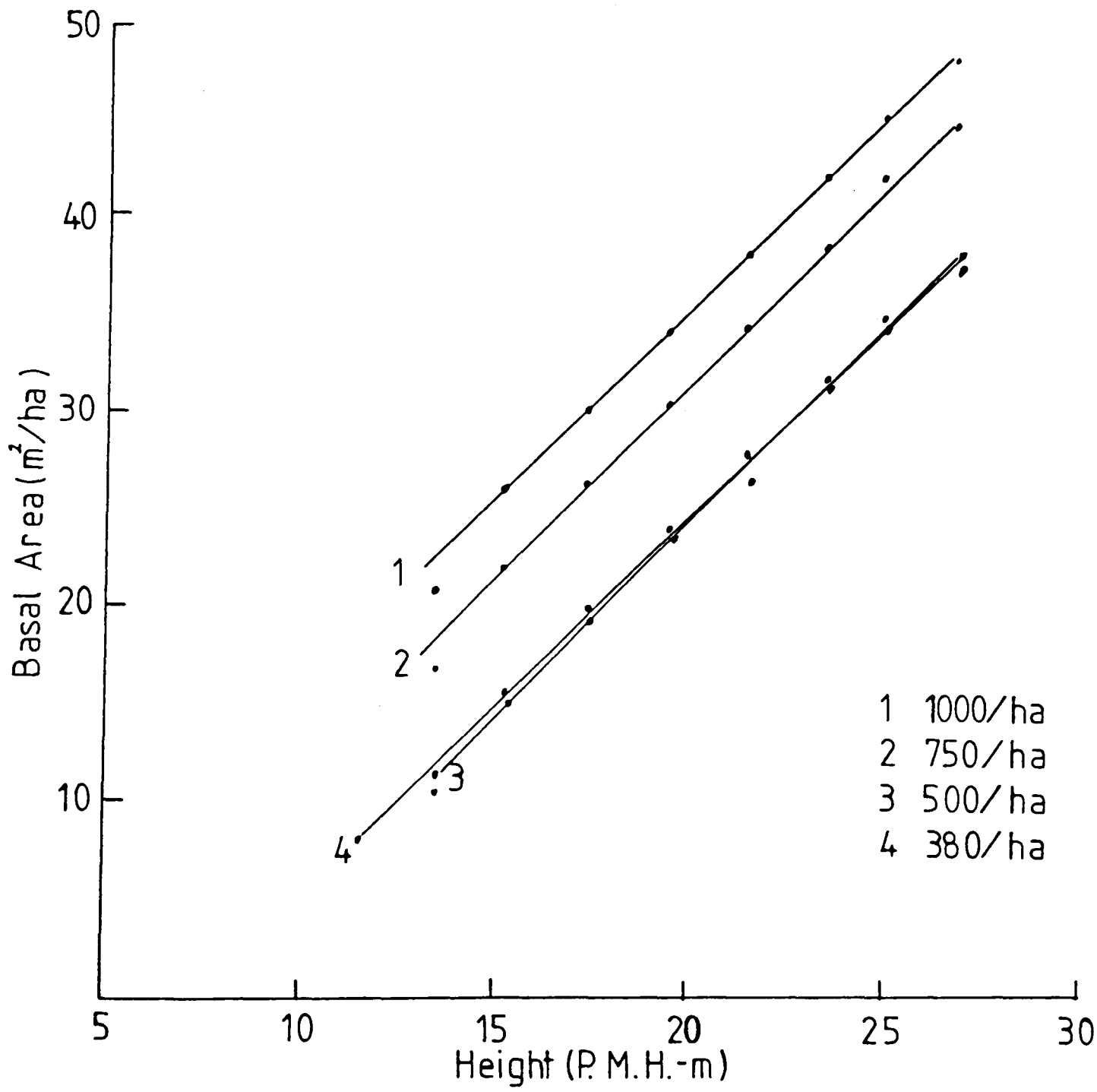
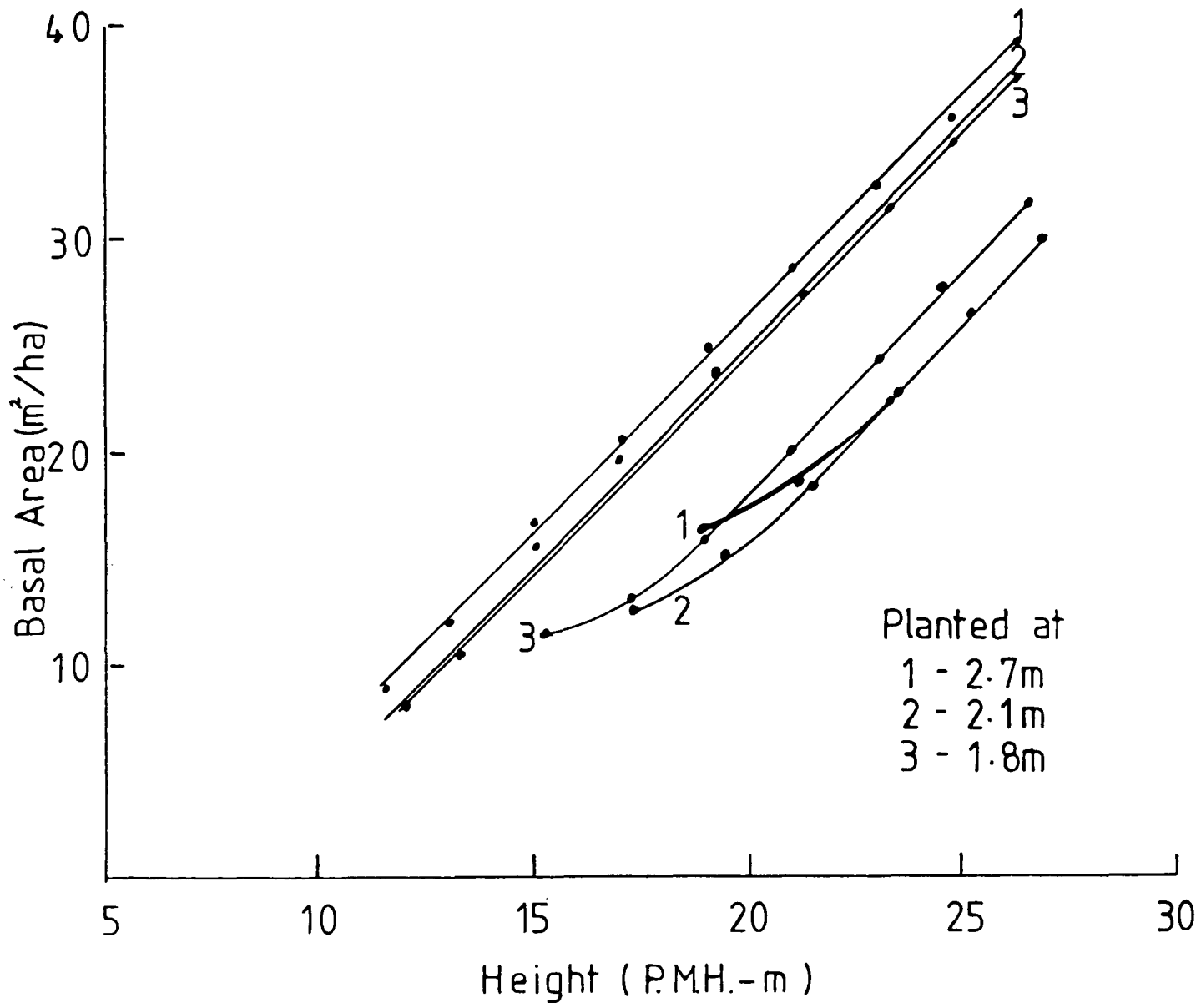


Figure 73 Thinned to 380/ha -'Early'and'Delayed' Thinnings



CHAPTER 8

PREDICTION OF FUTURE DIAMETERS

8.1 Existing Growth Models

In order to test the effect of differences in silvicultural regime on the distribution of volume by woodage, it is necessary to know how the changes in stocking level (whether by planting rate or by thinning) affect the distribution of growth to each tree in the stand. This can be done using a suitable growth model. Growth models can be divided into two major classifications (Munro 1974); stand level models and individual tree models. Individual tree models can again be subdivided into those which require a knowledge of the size of and distance to trees surrounding the subject tree (distance dependent models) and models which require knowledge of the distribution of tree parameters within a stand but do not require these to be known in relation to a given individual tree (distance independent models). At the commencement of this work, there were three basic growth models (and a number of variations) available for New Zealand radiata pine, all of them at stand level. The first to be developed was that of Beekhuis (1966) and was based on hand-graphed growth trends from permanent sample plots. The model is still used but is now regarded as unreliable for some regions. Also, many of the regimes currently practised fall outside the stocking limits set by Beekhuis for the application of his model. Elliot and Goulding (1976) developed a model specially for Kaingoroa State Forest. This was also based on data from permanent sample plots. It consists of a series of multiple regression functions and since its original development has been extended in use by the addition of three adaptations for other localities. In addition there are two models of specialised application. The foresters of Nelson

Conservancy have developed a model for their own region also based on multiple-regression functions (Tennant 1982); and Manley and Knowles (1980) presented a series of locally applicable regressions for basal area on height specifically for stands thinned to 178-227 stems/ha at about 12m height. The third basic type was the model by Clutter and Allison (1974); "the system is basically a stand-level simulator (but) the amount of detail generated is comparable to that produced by individual tree simulations". The model commences with an actual or predicted diameter distribution, growth in gross basal area, basal area mortality and stems per acre mortality are predicted annually. Output includes height and diameter class frequencies. The model is applicable only to forests owned by New Zealand Forest Products Ltd., and although the functions are published, the coefficients can only be obtained from the Company.

Since this study was begun, Garcia has completed two stand level models based on differential equations with parameters estimated by maximum likelihood methods (Garcia 1979, Tennant 1982) and two individual-tree models have been developed. These single tree models were developed contemporaneously with this work and copies have been supplied to the present author. Tennant's model (1981) is distance-dependant and can be used to predict the diameter, height and crown development of a stand of trees. The model is deterministic and for diameter increment a multiple regression equation is used with crown ratio, competition index and diameter at breast height as the independent variables. The model predicts mortality and allows for the effects of pruning and thinning.

The other individual tree model for radiata pine was developed by Manley (1981), his model is distance independent where "the diameter function has site acting as a multiplier on a linear combination of stand basal area, relative spacing, relative tree diameter and top height".

That is, a multiple regression equation in which the diameter of the subject tree was related to its place in the stand and the state of development of the stand itself was characterised. Manley compared his model (distance-independent) with Tennant's (distance-dependent) and found the comparison generally favourable to the distance independent model.

8.2 Choice of Model Type

Although existing stand level models can be used to provide a future diameter distribution (eg. Beekhuis (1976) who includes a diameter distribution table as part of his model); when testing the sensitivity of diameter growth to thinning schedule is to be a primary function of the model the use of models more directly concerned with individual tree growth is indicated. This is reinforced by Munro (1974) who states that single-tree/distance dependent models "are capable of producing very detailed information about the structure of the stand" and that single-tree/distance independent models can usually provide "detailed tree and stand information", and are capable of forecasting the response to thinning, spacing and sometimes fertilization.

Accordingly, it was decided to construct a single tree model and in May 1980 additional data were collected to facilitate this.

For every plot currently being measured the position of each tree was mapped using an x,y co-ordinate system with the origin at the plot centre. The 'x' axis being parallel to the planted rows and the 'y' axis at right angles to it. In addition, all possible competitors located in the 'buffer' zone were mapped and, as no measurements had been taken for these trees, diameter at breast height (outside bark) was measured.

With the important addition of the stand map, the data therefore represents only that normally available from a permanent sample plot series

(individual tree diameters and height sample). For the purposes of this study each plot was regarded as a sample of a particular regime. All attempts at modelling were done on a whole-of-plot basis where the growth of every tree within the inner plot was modelled at the same time. An example of the diameter and location data available for one plot is given in Appendix 4.

8.3 Development of a Competition Index

A common feature of all individual tree models is the 'competition index'. This is an index of stand and/or tree parameters devised by the various authors with the aim of explaining more of the variation in tree growth than can be explained by tree diameter alone. Although empirical in nature, they are an attempt to reflect biological parameters thought to control tree growth or inter-tree competition. Allemdag (1978) classified the types of competition indices used in distance-dependent models into five groups, depending on the parameters used to construct the index. They are:

(i) Crown (or adjusted crown) overlap of the subject tree with neighbouring trees. (Various authors have used distance of overlap, angle of overlap, or area of crown overlap.)

(ii) Single-tree density in terms of basal area around the subject tree.

(iii) Available growing space around a tree.

(iv) Diameters and/or distances to neighbouring trees.

(v) Crown surface and height of subject tree.

Allemdag (1978) tested six of these indices, (four chosen from groups 1, 3 and 4, plus two he devised himself), as predictors for the growth of planted white spruce (Picea glauca (Hoench) Voss) in Canada. He noted that "the correlations between (all of) these competition indices and

future diameter increment are very poor" and "the competition indices alone did not always show superiority over diameter in estimating increment".

The type of index tested and eventually developed for the model presented here could be classified in Alemdag's group 2, single-tree density. From common observation it was noted that within an even aged stand there is a range of diameter increments. It is argued that this is because:

(a) some trees are genetically better (or worse) suited than others to the site;

(b) that microsite variation, (local slope or soil depth for example), aids or hinders growth on some trees more than on others;

(c) the spatial arrangement of the trees means that a given individual tree receives more or less than average of the necessities of plant life (sunlight, water, soil nutrients);

(d) these effects interact with each other and that each tree does not grow in isolation but competes with others also subject to these effects.

The objective in developing the competition index was to derive, by empirical means, a parameter which would reflect both category (c) - the advantage (or otherwise) gained by each tree from its spatial arrangement in the stand, and (d) the interaction with other trees. As a working hypothesis it was decided that "surrounding each tree is an area of 'competition catchment' within which potential competitors lie and from outside which trees do not compete with the subject tree. Also that the area of this competition catchment increases with tree dimensions". As a first approximation the competition catchment was defined as a circle with its centre at the subject tree and a radius derived from the formula

$$y = \frac{x}{a + bx}$$

where y = radius in metres and x = stand PMH in metres. The radius thus calculated, at first increases rapidly with increasing height then slowly until an asymptotic value is reached. By adjusting the values of a and b the shape of the curve and the maximum value of the radius can be altered. Testing was confined to curves which gave values within the range 4 to 10 metres at PMH 25 metres (at which height the radius is close to its maximum value). Three plots were chosen subjectively as pilot data and a computer program written to derive, year by year, for each tree within each plot in turn: one of a series of competition indices, the increment of that tree and to graph the relationship between the two. From inspection there appeared to be a good correlation between individual tree increment (in basal area) and indices that involved summing the basal area of competing trees (i.e. trees within the competition catchment). The three plots chosen for this initial evaluation were all planted at 2.7m, two were thinned (to 375 and 750 stems/ha) and one remained unthinned. They contained 23, 45 and 95 trees respectively and had been measured for 12 (two plots) or 11 years thus giving 32 increment periods in total (1748 tree x increment periods).

To provide an objective test for the correlation of the indices, annual growth was regressed against tree basal area at the beginning of each year using the Oxford Forestry Department's computer package 'NONLIN'. This package, which is described in detail in Appendix 2, is used to derive non-linear relationships between two variables by iterative procedures. Twelve possible models are tested and in this case the one most often selected as best had the form

$$y = a\,(1-e^{-bx})^{c}$$

where y is annual increment per tree;

x is tree basal area

a, b and c are constants.

The coefficients of determination between tree basal area and increment are given in Table 8.1.

Table 8.1. Coefficients of Determination - Increment with Basal Area

Time Period	Thinned 380/ha n = 23	Thinned 750/ha 45	Unthinned 1500/ha 95
1969-70	0.775		0.492
1970-71	0.726	0.422	0.501
1971-72	0.681	0.583	0.600
1972-73	0.685	0.710	0.699
1973-74	0.658	0.569	0.685
1974-75	0.722	0.541	0.709
1975-76	0.700	0.645	0.654
1976-77	0.617	0.696	0.655
1977-78	0.618	0.644	0.719
1978-79	0.611	0.651	0.714
1979-80	0.640	0.766	0.718

The values for r^2 are sufficiently high to regard this correlation as firmly established. Work then concentrated on devising an index of competition which could be used as a multiplier with tree basal area and which would thus improve the amount of explanation. It was thus hoped to derive a series of equations describing homologous curves linking increment and tree size and for which the coefficients in the equations would vary predictably with time.

The indices investigated were:

1. $\frac{\Sigma G}{g}$

2. $\frac{\Sigma G}{g^2}$

3. $\frac{\Sigma (Gx(R-l))}{g}$

4. $\frac{\Sigma (Gx\frac{1}{l})}{g}$

5. $\frac{\Sigma (Gx(R-l))}{g^2}$

6. $\frac{\Sigma G^2}{g}$

7. $\frac{\Sigma Gx(R-l)^2}{g^2} \; / \; (R/_2)^2$

8. ΣG

where G = the basal area of a competing tree

g = the basal area of the subject tree

R = the radius of the competition catchment

l = the distance between the subject and competing tree

The definition of a competing tree was varied: by altering the function that determined the radius of the competition catchment, by taking only the nearest or largest so many trees within the competition catchment as competitors and by taking only the nearest or largest so many trees per quartile (i.e. 90° segment) as competitors. The number of possible combinations of all these effects is very large and not all were tried. The best combination found was: competition index defined as

$$\frac{\Sigma G}{g^2} \quad ,$$

competing trees being the closest two trees per quartile within a circular competition catchment of variable size that extended to 10m radius for a stand of height (P.M.H.), 25 metres. When used as a multiplier with tree basal area and regressed against increment, the result was an increased r^2 for some years, decreased for others and overall a slight improvement.

The improvement was, however, judged to be too small to justify this approach so the attempt to explain increment by a set of homologous non-linear curves was abandoned. The next phase was to build a model based on multiple linear regression analysis.

Both tree basal area and the competition index were retained for this next phase. This was because their correlation with increment had been established and there appeared to be good biological reasons for linking them with increment. At a given age tree basal area is the sum of all the preceding years' increments. Unless the competitive status of the tree changes dramatically it should thus also indicate succeeding increment. Expressing the total size of competing trees as a ratio of the size of the subject tree is an attempt to indicate competition pressure, independent of the actual size of the trees involved.

8.4 Development of the Diameter Model

Using the same three plots as used in phase one to provide pilot study data, individual tree basal area increment was regressed against a number of independent variables using the computer package ANDRESS. This package calculates multiple linear regressions and can be used to test the significance of variables, eliminating those that are not significant and recalculating the relationship. Many new variables were

tested to supplement the two already established in stage one. Finally a seven variable regression involving tree basal area, competition index, a 'growing space index' and interactions of these variables was obtained and compared with the results of regressing increment with tree basal area alone (see Table 3).

Table 8.2. Coefficient of Determination: Increment/7 variables

Time Period	Thinned 380/ha n = 23	Thinned 750/ha 45	Unthinned 1500/ha 95
1969-70	0.860		0.591
1970-71	0.852	0.623	0.545
1971-72	0.765	0.703	0.635
1972-73	0.746	0.772	0.723
1973-74	0.734	0.656	0.702
1974-75	0.795	0.612	0.753
1975-76	0.753	0.687	0.723
1976-77	0.761	0.706	0.722
1977-78	0.740	0.664	0.797
1978-79	0.685	0.687	0.813
1979-80	0.723	0.787	0.803

Coefficients of Determination were increased and although this increase was not always large, (about 0.1) it invariably occurred. The greatest increase occurred where tree B.A. alone had given a low explanation and all values of r^2 were above 0.5 indicating that in no time period did the regressions fail to account for less than half the variance in the increment.

After considering these results it was decided that for the data available as a result of this field experiment, the best approach towards deriving an individual tree model for diameter increment would be to continue with multiple linear regression analysis.

8.5 Screening Increment Values

Another result of this first stage of investigation was to demonstrate the need to screen increment values derived from diameter measurements. The diameter of every tree in this experiment was carefully and competently obtained using a standard forestry diameter tape at breast height (1.4m in New Zealand). All data had been checked with the aid of a routine in the New Zealand Forest Service Permanent Sample Plot computer package. This program uses moving averages to identify values likely to be anomalous and all gross errors (such as 'shrinking trees') were corrected before the data were used in this study. The diameter values were therefore 'accurate' within the normal limits of sample plot inventory and provided satisfactory estimates of tree diameter at each date of measurement. When a time series of measurements was converted to basal area and subtracted to give annual increment values, the results sometimes showed large and almost certainly unnatural fluctuations. This is a recurrent problem in estimating increment and arises because a small under- or over-estimate in diameter could represent a large increase or decrease in derived basal area increment. While it was important to restrict extraneous variation it was also necessary to derive a data set which contained all the changes in increment that might be due to natural causes such as competition or age. Accordingly, data were screened using a moving average system. Three consecutive increment values were considered, an average of all three obtained and the second value tested to see that it lay within $\pm$30% of the average. If it did, no change was made and the check was repeated incorporating the next value (fourth) and dropping the first value; and so on. If the second increment was outside the 30% limit it was set as the average of the second and third increments and the third increment was set to equal the second. That is an erroneous measurement was assumed, and as this would affect two increment values

equally and in the opposite sense, the values were adjusted by setting both to the mean of the two. Adjustment in this manner meant that the total increment for any given tree remained constant. The criterion for deciding whether an anomaly had occurred was formulated from inspection of hand-graphed increment fluctuations for 23 trees. Neither the first nor last increment can be checked in this manner. All the models presented here are based on data screened by this method.

8.6 Growth of Trees in the Buffer Zone

As well as screening increment values for trees within each plot, it was also necessary to provide values for trees outside the limits of the inner plot. As mentioned in the description of the data source, each inner plot containing trees of known diameter over time was surrounded by a 'buffer' of trees at exactly the same stocking but not measured before the stand mapping in 1980 at 17 years of age. Trees from within the inner plot but located close to the inner/outer plot boundary could have up to half their competitors located in the buffer. To calculate early values for competition index it was necessary to model the past growth of outer plot trees; this is the reverse of the usual problem where future growth is required. For the pilot studies described earlier a crude linear model was used.

Since the trees in the outer plot are the same age and genetic composition as those in the inner plot, data from the regularly measured trees was used to construct the model. Examination of the growth of selected trees by hand plotting showed that for both fast and slow growing trees the increase in diameter with time was non-linear. For the slowest growing trees growth had virtually ceased by 17 years and the curve was asymptotic. The fastest trees, although slowing in growth with time, had not yet reached the point where the growth curve was levelling off. Trees with the same

diameter at 17 years but different treatment histories showed variation in juvenile diameter growth.

Four plots were chosen as the data base, selected to give a large range of individual tree growth rates.

Table 8.3. Data for Out-of-Plot Model

Spacing at Planting (m)	Treatment	Stocking (stems/ha)	Plot No.
1.8 x 1.8	unthinned	3000	20
2.7 x 2.7	unthinned	1500	15
2.1 x 2.1	thinned once	750	6
2.7 x 2.7	thinned once	380	4

In total the four plots contained 250 trees. Data from these trees were sorted into 50mm diameter classes (at age 17) within each plot and this is shown in table 6.

Table 8.4. Number of Trees by Size and Stocking at 17 years Diameter Classes (mm)

Plot Stocking	100	150	200	250	300	350	400	450	500+
3000	6	28	31	21	10	6	1	-	-
1500	1	10	26	15	16	10	1	1	
750	-	-	6	11	8	13	4	1	1
380	-	-	-	1	1	4	9	7	1
n =	7	38	63	48	35	33	15	9	2

Average growth trends (diameter with age) were calculated for each 50mm class within each plot to give 28 growth curves. These were regressed against age using the NONLIN package. Combining the data to derive average growth trends for each size class had removed most of the variation and

r^2 values for many of the models were extremely high. The model most commonly having the best fit was of the form

$$y = a + be^{-cx}$$

In spite of the known differences in juvenile diameter according to previous treatment, data were combined into 50mm classes (at 17 years) regardless of origin. This was principally because trees located in the buffer zone between plots are by definition subject to the influence of more than one treatment schedule. Those trees in the outer plot but located close to the inner plot boundary will be mostly under the influence of the regime for the whole plot, those located close to the junction of another plot will be partly under the influence of the treatment regime for that plot. As the plots are hexagonal in shape any given plot could be bounded by up to six different regimes. Predicting the growth of 'buffer-zone' trees must be approximate at best. The investigation which formed part one of these studies revealed that under all the many definitions of competition catchment no tree had more than half of its competitors located in the buffer zone.

Regressions were calculated for each class using the equation given above. It was seen that the coefficients all varied in a regular manner with respect to size class. Again using the NONLIN package the change in the value of each coefficient with size class was modelled. (Values for r^2 were greater than 0.9.)

The regression equations were combined in a short computer program and tested to see if predicted diameters matched the original data. They were found to conform well to the data in terms of the shape of the curve but to consistently under-estimate all values including values for 17 years, the initial data point. The model was changed so that coefficients

Table 8.5. Combined Growth Data, Out-of-Plot Model (D.B.H. (ob)(mm))

Class (mm)	Age 6	7	8	9	10	11	12	13	14	15	16	17
100	98	102	106	106	109	109	109	109	109	109	109	109
150	123	130	136	140	144	147	149	151	150	152	153	153
200	145	155	166	175	178	184	188	191	193	196	199	199
250	155	166	181	192	202	211	220	227	232	239	245	249
300	164	179	197	211	224	238	249	260	268	279	288	296
350	176	190	216	237	255	272	288	301	313	327	338	349
400	178	209	246	272	296	317	333	349	363	377	390	401
450	195	225	264	293	320	339	363	382	400	418	430	444
500+	188	229	273	303	336	352	385	416	429	447	466	486

b and c were predicted by non-linear regression based equations and the value for a found by substitution in the main equation using the known value for diameter at 17 years. This improved the prediction although a small negative bias remained in all but the smallest and largest age classes. This last source of bias was removed using an equation of linear form, based on a regression of bias against age. Predictions then conformed closely to the actual data. Due to the structure of the experiment, there is no independent source of growth data for trees located in the buffer-zone between plots; because of this the model could not be further validated. However, in view of the role of this routine in the total model (i.e. to calculate the size of some of the competitors of some of the trees to be modelled) this was considered acceptable.

The equation used to predict coefficient b was of quadratic form ($y = a + b + cx^2$) and that used to predict coefficient c had the form $y = 1/(a + be^{-cx})$.

The section of the model program in which the past diameter for an out-of-plot tree is calculated is given below. The program is written in FORTRAN.

```
 1   C CALC PAST DIA FOR TREE OUT OF PLOT
 2         AGE=17-(MEASNO-M)
 3         X=(DOUT(D)/0.05)-1
 4         CB=-1*(0.08759774+((X*0.0434391)+(0.004444384*(X**2))))
 5         CC=(1/(18.16906+(-18.76254*(EXP(-0.1311164*X)))))
 6         CA=DOUT(D)-(CB*(EXP(-CC*17.0)))
 7         Y=(CA+(CB*(EXP(-CC*AGE))))
 8         IF(X.LT.1.49) GOTO 804
 9         IF(X.GT.8.50) GOTO 804
10         BIAS=(17.5056-(1.23167*AGE))/1000
11         IF(BIAS.LT.0.0) BIAS=0.0
12         Y=Y+BIAS
13     804 R=Y/2
```

Where: DOUT(D) = diameter of Dth tree

CB = coefficient b

CC = coefficient c

CA = coefficient a

BIAS = bias

AGE = age in years

This routine was used both when developing the diameter model and in the model itself.

8.7 Definition of Variables

With the decision to concentrate on multiple linear regression the data base was enlarged to seven plots, subjectively chosen to include a wide range of stocking rates, and an attempt was made to create new variables that had some basis in forest biology. The expanded set of pilot data included stocking levels up to 5000/ha, and contained a total of 75 increment periods. Only the first 23 trees from each plot were used (1725, tree x increment periods). All plots and time periods were kept separate for this stage of the investigation. One of the concepts tried at this stage but not included in the final model was that of

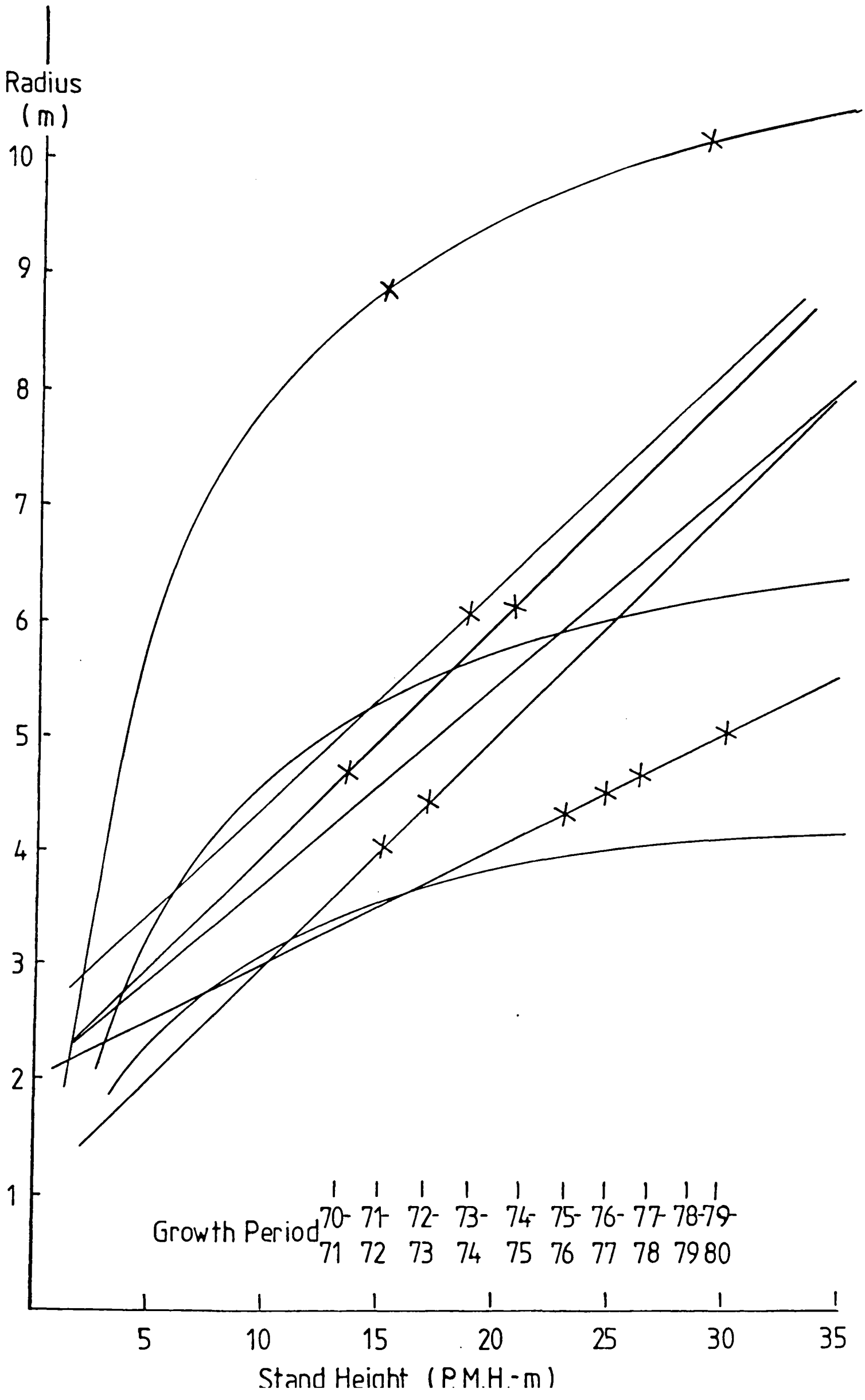
localised density. That is where density (in basal area) was obtained for the area immediately surrounding the subject tree. By this means it was hoped to assess the growth potential of the microsite in which the subject tree was located. However, when expressed as the live basal area within a circle of 1/100 or 1/200ha in area with the subject tree at the centre, or as the ratio of actual local basal area and average local basal area for the plot, it was only occasionally found to be a significant variable in the multiple linear regressions. Unsuccessful attempts to devise a more responsive index of competition included subtracting four times the subject tree basal area from the competing basal area ($\Sigma G - 4g$) and dividing the competing basal area by six times the subject tree basal area ($\frac{\Sigma G}{6g}$). Attempts were also made to create a growing space index. These included functions of mean distance to competing trees, functions involving the radius of the competition catchment and mean distance to competitors, and a function based on the difference between actual growing space and the growing space required for 'free-growth'. (The space required for free growth was estimated from a plot that was not part of this experiment but located within it and reduced to 200 stems/ha). Functions involving the number of competitors and their distance from the subject tree were also attempted. The variables thus derived were tested by inclusion in multiple linear regressions for the 75 growth periods covered by the test data. All were rejected, mostly because their occurrence as significant variables was infrequent and haphazard but also because the same biological concept could often be expressed in very simple terms. This does not mean the concepts are invalid, for example, that growing space does not influence increment, or that with more parameters measured in the field some measure of (say) growing space that was consistently correlated to growth could not be developed. However, with the data

available, that is normal stand inventory plus stand map, the various biological concepts that probably influence growth could not be characterised by indices which were highly and invariably correlated with increment. The concept of growing space is, for example, represented in the model by the mean distance to competitors.

The definition of some of these indices depended on the size of the so-called competition catchment at each age. As previously described the limits of this catchment were, as a first approximation, calculated by an equation giving a curve rising to an asymptotic value. Although the dimensions of the curve were widely varied no size or shape was clearly better than the others. Alternative models based on linear relationships were also tried but again no one model was clearly superior. The way in which the radius of the competition catchment changes with time was finally determined by plotting this change for nine radius models, using each of the models to calculate the variables for a plot thinned to 750/ha; then noting the model for which the radius was associated with the highest value of r^2 for each year. This is illustrated in Figure 8.1. The result is clear, but surprising; the radius does not appear to vary with time but remains constant at about 5m. For this plot 5m is approximately the distance between trees diagonally opposite if 750 stems per hectare were arranged in regular square spacing.

This method of calculating the radius of the competition catchment, based on the live stocking at the beginning of each year, was tested for a range of stocking levels. Coefficients of determination were increased and the method was adopted both for further investigations and for the final model. This means that the hypothesis, that the size of the competition catchment increases with time, was rejected.

Figure 8.1 Radius of Competition Catchment with Highest r^2



From earlier analysis at plot level, it was known that immediately after thinning, trees suffer a reduction in increment (see Figure 7.3). A dummy variable indicating the first year after thinning was incorporated and found to be significant.

With only simple variables used, the data from all plots were combined, each year being kept separate. By combining plots with a range of stocking levels, the range in values of the derived variables was increased and consequently the value of t for each variable increased. The coefficient of determination for each regression also increased. The data were then combined for all years and age itself introduced as a variable. The coefficient of determination still remained high at 0.77. It was therefore concluded that the data could be combined across all stocking levels and for all ages and that a multiple linear regression using some of the simpler variables developed with the pilot data would be sufficient to provide a satisfactory exploration of increment.

8.8 Sampling the Data

The last phase in the development of the diameter model was begun by deriving a new data set involving all plots in the experiment. Of the three replicates for each silvicultural schedule, one was chosen at random to form a set of data for validation; the remaining two provided the main data set for model derivation. One plot from each of the two data sets was later rejected because of anomalies, this left a total of 50 plots for the main data and 24 for validation. As the main data set contained about 2,700 trees and this would provide approximately 26,000 increment periods, it was decided to sample the data in proportion to variance. From the earlier analyses at plot level it was known that initial stocking had very little effect on basal area growth after thinning (see

Figure 7.3). Thus the data were grouped into 13 silvicultural classes based on thinning schedule.

Table 8.6. Data Grouped by Silvicultural Class

Regime		Number of Plots	Total Trees	Sample No.
Thinned early,	380/ha	6	138	22
Thinned late,	380/ha	7	161	24
Thinned late by rows,	380/ha	6	138	25
Thinned twice,	380/ha	6	138	21
Thinned early,	500/ha	2	60	21
Thinned early,	750/ha	7	315	19
Thinned early,	1000/ha	2	120	19
Crown thinned,	500/ha	2	60	22
Thinned early,	1350/ha	2	162	15
Unthinned,	1500/ha	2	198	19
Unthinned,	2200/ha	2	292	18
Unthinned,	3000/ha	2	327	15
Unthinned,	5000/ha	2	609	25
		50	2744	265

That is, plots which had been planted at different stocking levels but which had received the same thinning treatment were included in the same class. In order to sample the 13 classes in proportion to their variation, the mean variance of the square of oldest live diameter for each tree in every plot in the class was calculated. This parameter was chosen because it reflects both the variation in increment and of the principal predictor variables in each class.

About 10% of all trees were taken to give a total of 265 sample trees chosen at random, the number from each class being shown in Table 8.6. Each sample tree once chosen was used to provide dependent and independent

variables at all ages; one tree could therefore supply up to eleven annual data sets. Although this meant that the observations were not all strictly independent of each other, it was felt that a model developed from such a data set would be more realistic, since the data source would then exactly correspond to the situation to be modelled.

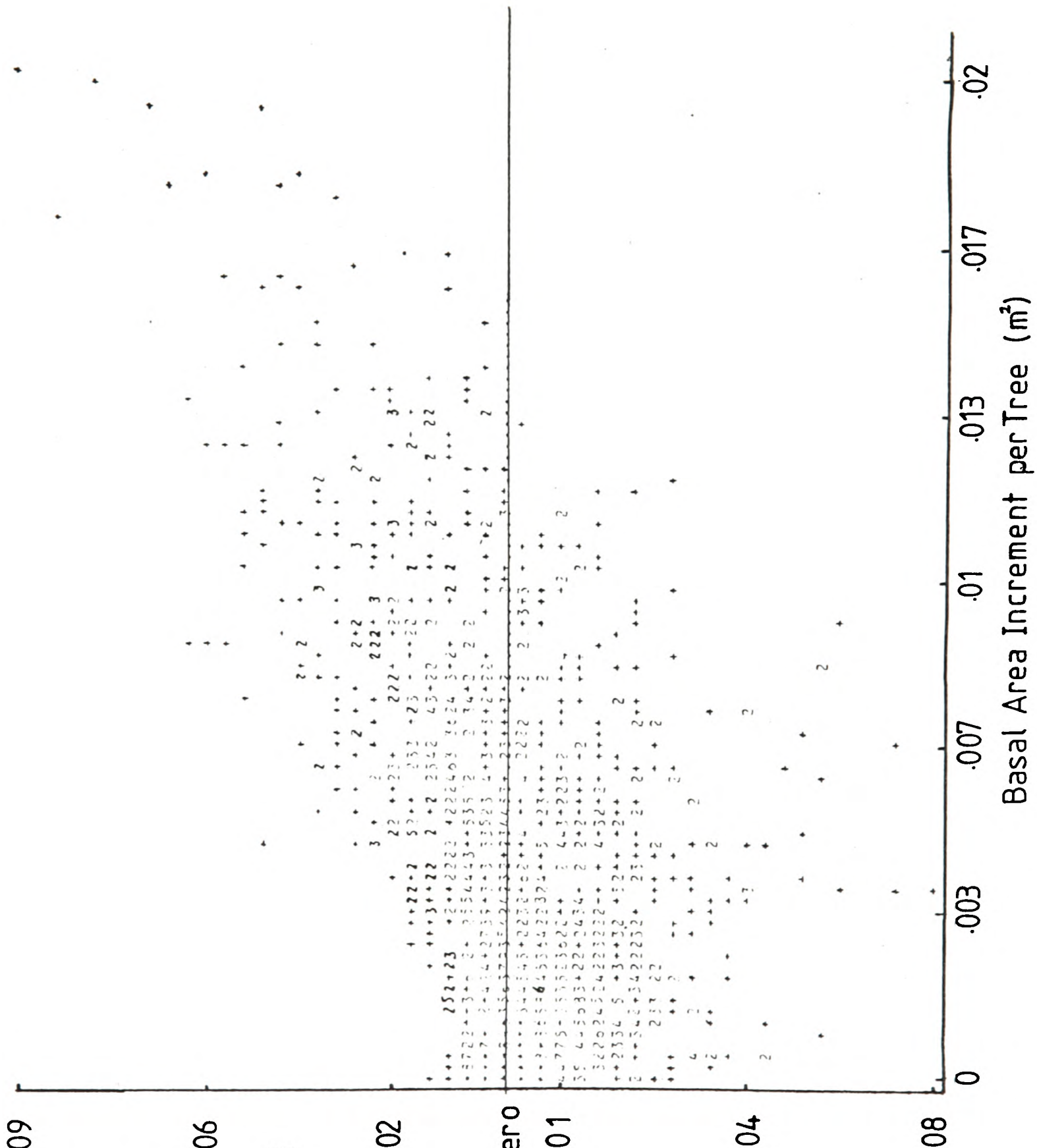
8.9 Deriving the Model

The total number of increment periods (trees x annual increment periods) contained in the final data set was 2,300. For the derivation of the final model the CGMP computer package was used. This is a multiple linear regression package which includes a facility for graphical presentation. This package was also used with the expanded pilot data where the graphical facility was used to display the distribution of residual variation.

When regressions were developed using untransformed variables, 'error' or variation not explained by the derived regression equation was distributed asymetrically. This is illustrated in Figure 8.2 and shows that large values of increment would be consistently underestimated and that the derived equation was quite unsuitable for predictive purposes. A number of transformations were tried for the independent variables, none however resulted in a better distribution of residuals. Transforming the dependent variable, by taking the natural logarithm of increment, solved this problem (Figure 8.3).

Although trees which are suppressed but alive within a stand may grow in height and in stem diameter in the region of the crown, growth at breast height may be undetectable. Many such trees in this experiment were correctly assessed as having periods of zero basal area increment. This posed a statistical problem in that many combinations of independent variables resulted in the same constrained value of zero. This contradicts

Figure 8.2 Distribution of Actual - Predicted Values for Increment Using Natural Values



the assumption underlying a linear correlation; that the value of the dependent variable varies freely with changes in the value of the independent variables. For this reason, all values of zero increment and 32 values near zero which contributed excessive error were removed from the data, reducing the total number of data sets by 5.5% to 2,260. Zero basal area increment is, however, a legitimate value in nature and the manner in which this value was predicted is described in the section dealing with the prediction of mortality.

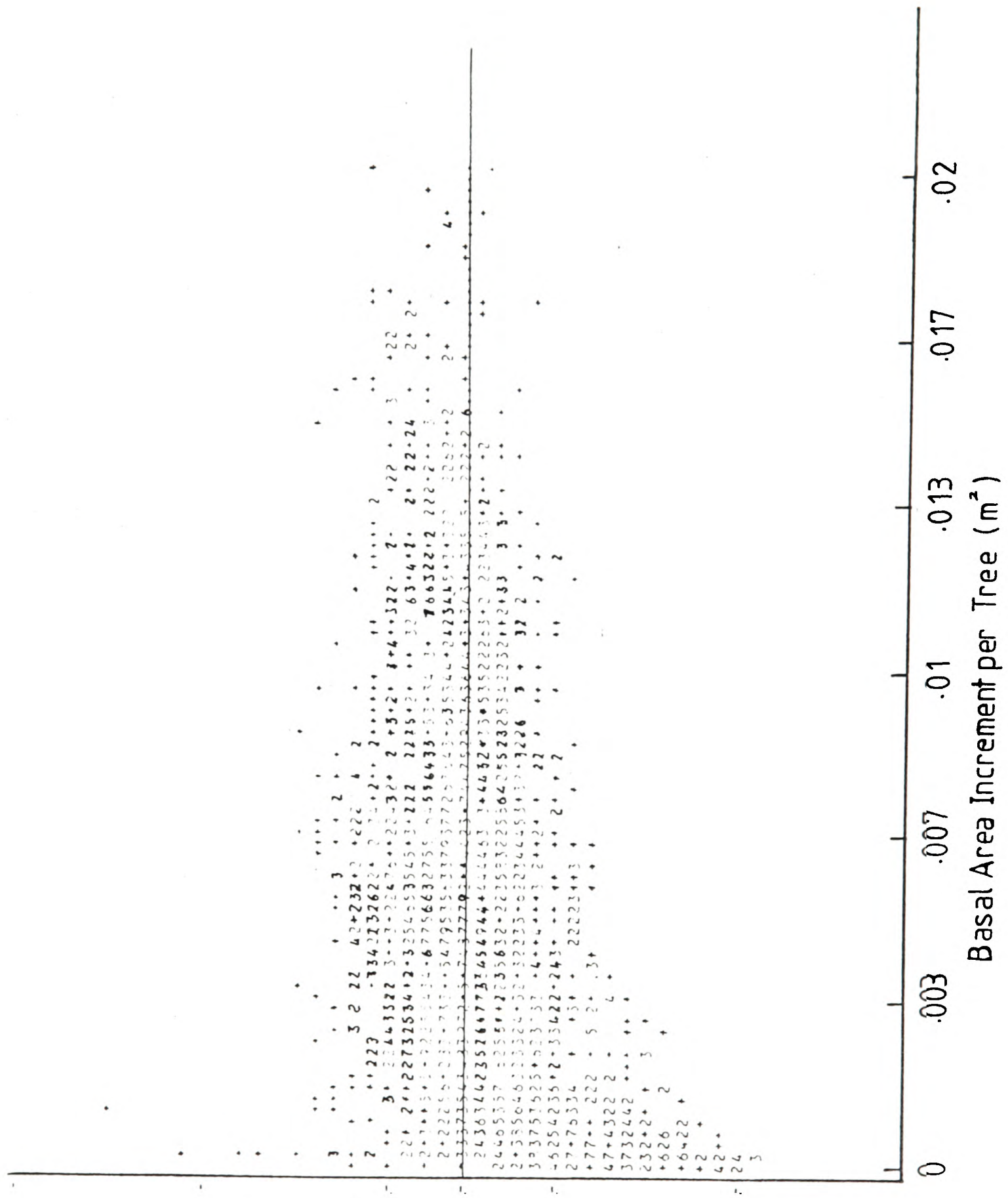
The equation thus derived to predict the natural logarithm of increment was:

Variable	Coefficient	Standard Error	T-value
Intercept	-6.2621	0.1487	-42.12
Competition	-0.2160	0.0106	-20.31
Basal area	55.3134	2.8033	19.73
Mean distance	0.5571	0.0437	12.74
BA squared	-569.7609	49.0165	-11.62
Comp. x mean dist.	0.0288	0.0025	11.31
Age	-0.1273	0.0134	-9.53
Thin	-0.4594	0.0532	-8.63
Age x BA^2	21.3405	2.5407	8.40
Age x mean dist.	-0.0267	0.0038	-7.02

$r^2 = 0.763$

Where: Competition is the sum of basal area of competing trees divided by the basal area of the subject tree ($\leq G/g$); basal area, is the basal area of the subject tree; mean distance is the mean distance to competitors; age is the age in years; and thin is a dummy variable with the value 1 if the stand has just been thinned, zero otherwise.

Figure 8.3 Distribution of Actual - Predicted Values For Increment Final Equation (log_e values)



The distribution of 'error' (actual-predicted values) obtained with the final equation is shown in Figure 8.3. Calculating the regression with the natural logarithm of increment as the dependent variable has resulted in a much improved distribution of error and has almost entirely removed the tendency to under-predict the higher values.

8.10 Testing the Model

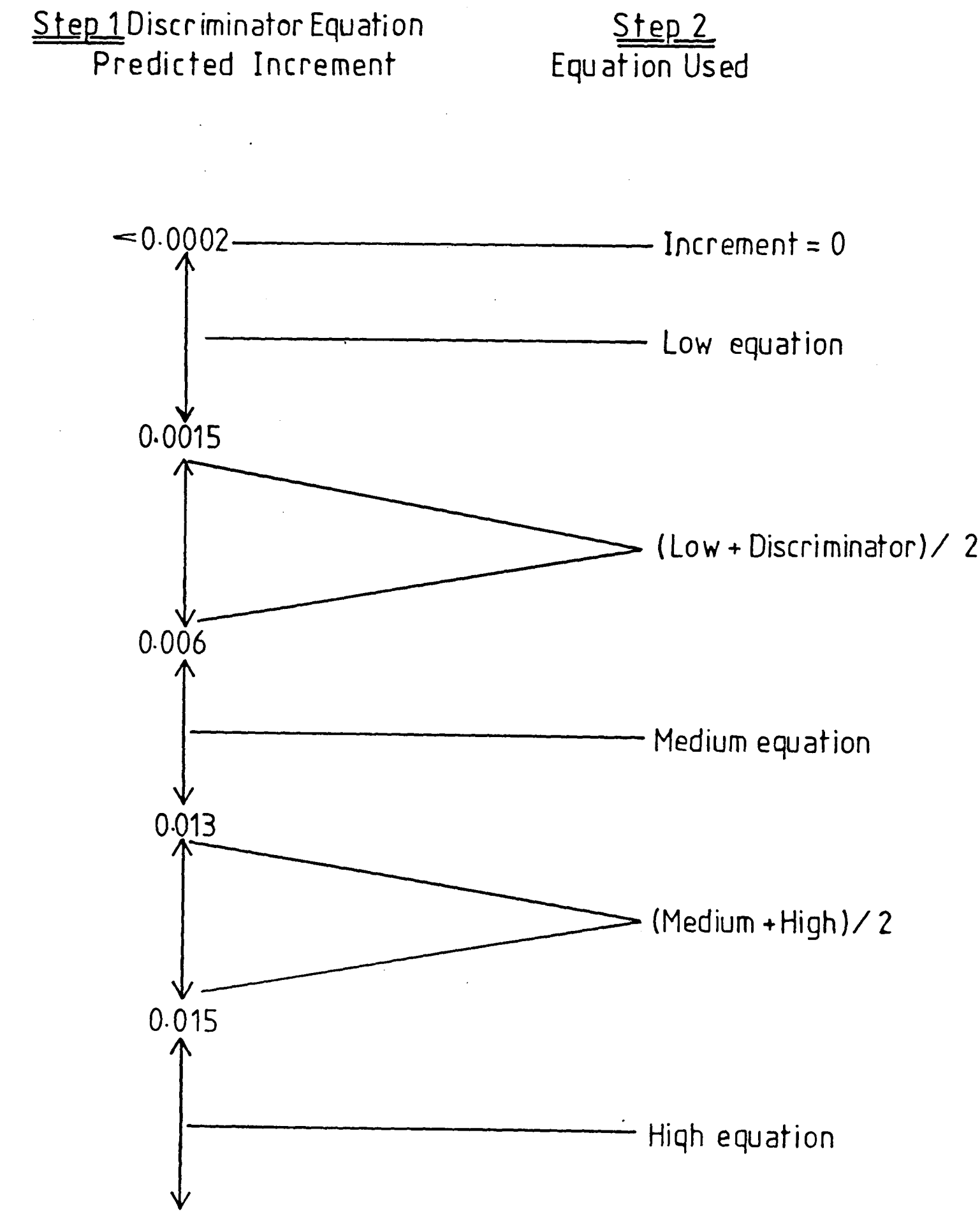
The equation given above was incorporated into a computer based model of individual tree growth. As only 10% of the trees in the main data set had been used to provide the data from which the model was derived, plots were selected from this set for the initial comparisons. Throughout the testing and validation, comparisons were made on a whole-of-plot basis, the growth of all trees within the plot being predicted. The test plots were chosen to provide a range of stocking levels and it became apparent that the model did not predict all stand densities equally well.

Although the model was a good predictor for all but the most dense unthinned stands and for stands reduced to no less than 750 stems/ha, for all plots reduced to a lower stocking the model was unsatisfactory. For these plots increment and hence tree diameters were strongly over-estimated. Since this bias was quite pronounced the original data were divided into three groups based on observed increment; increment greater than $0.01 m^2$/ann, 0.01 to $0.003 m^2$/ann and 0.005 to $0.0 m^2$/ann; and new equations developed for each group.

The strategy adopted was to predict increment with the general equation and use this value to assign the subject tree to a high, medium or low increment group. Actual increment was then recalculated by one of the more specialised equations. This system proved to be successful and, with modifications, was the strategy adopted in the final model. The

bias resulting from the general equation used to discriminate between increments necessitated adjustment in the boundary values between the three groups. The boundary to the high increment group was adjusted upwards to compensate for the over-prediction of high values and the boundary for the lowest group adjusted down to compensate for under-estimation of the lowest values. The result was realistic values but for some plots discontinuity in the range of predicted values. This was due to the natural variation in actual values to be expected around any predicted value and the abrupt definition of the class boundaries. A tree might, for example, actually have an increment slightly higher than predicted by the discrimination equation. If this resulted in incorrect allocation to the middle or lower increment groups its increment would be under-predicted by the specialised equation. Since the model proceeds in annual steps the error is likely to be repeated, and accentuated, on each successive occasion. When the clear-cut boundaries between increment groups were replaced by broad-bands of transition, the problem of discontinuity was aleviated. Trees with increment assessed as being within the band of transitional values have their final increment values derived from two rather than one of the specialised equations. The equation for medium values gave biased results when used for low values so the discrimination equation was used in the low-medium transition band. The final allocation to equation is shown in Figure 8.4.

Figure 8.4 Allocation to Increment Equation



The equations are:

Variable	Coefficient	Standard Error	T-value
'High Equation'			
Intercept	-4.6710	0.07092	-65.86
Mean distance	0.1075	0.01930	5.57
Competition x distance	0.006742	0.001291	-5.22
Basal area	1.3824	0.5457	2.53
Age x distance	-0.003138	0.001339	-2.34
Thin	-0.09468	0.04628	-2.05
r^2 = 0.16 n = 18% of total			
'Middle Equation'			
Intercept	-5.7533	0.1059	-54.17
Mean distance	0.02558	0.002828	9.04
Competition	-0.03749	0.004833	-7.76
Basal area	10.5466	1.6906	6.24
Thin	-0.1603	0.03242	-4.95
Basal area sq.	-37.8018	9.8310	-3.85
Age x distance	-0.008868	0.002376	-3.73
Age	-0.02180	0.01033	-2.11
r^2 = 0.35 n = 57% of total			
'Low Equation'			
Intercept	-5.7498	0.1539	-37.36
Age	-0.2582	0.01631	-15.83
Basal area	95.3701	7.9002	12.07
Competition	-0.1746	0.01638	-10.66
Basal area sq.	1474.932	208.2912	-7.08
Competition x distance	0.02472	0.004299	5.75
Age x BA sq.	54.7648	10.4000	5.27
Mean distance	0.2077	0.0508	4.09
Thin	-0.4118	0.1053	-3.91
r^2 = 0.61 n = 54% of total			

All variables are as previously defined.

That part of the model which deals with the calculation of increment is given below.

```
C CALCULATE INCREMENT FOR TREE
      PART1=0.0
      PART3=0.0

C DISCRIMINATOR EQUATION
      ANS=(BA(N,M)*55.31344)-(COMP*0.215962)-(G2*569.7609)
     1+(AG2*21.3405)+(CD*0.0287 8043)-(AGE*0.1272772)+(DIST*0.5571002)
     2-(AD*0.02667115)-(THIN*0.4594533)-6.262149
      IF(ANS.LT.-16.118096) ANS=-16.118096
      DIS=EXP(ANS)
      IF(DIS.GT.0.006) GOTO 935

C LOW EQUATION
      ANS=(BA(N,M)*95.37013)-(COMP*0.1746338)-(G2*1474.932)+
     3(AG2*54.76479)+(CD*0.02472496)-(AGE*0.2582342)+(DIST*0.2076688)
     4-(THIN*0.4117763)-5.74979
      IF(ANS.LT.-16.118096) ANS=-16.118096
      ANS=EXP(ANS)
      IF(DIS.GT.0.0015) GOTO 955
      IF(ANS.GT.0.00015) GOTO 900
      ANS= 0.0
      GOTO 900
  955 PART1=ANS
  935 IF(DIS.GT.0.015) GOTO 945

C MEDIUM EQUATION
      ANS=(BA(N,M)*10.54657)-(COMP*0.03748523)-(G2*37.80181)
     2-(AGE*0.02179714)+(DIST*0.2557503)-(AD*0.008868142)
     3-(THIN*0.1603143)-5.73553
      IF(ANS.LT.-16.118096) ANS=-16.118096
      ANS=EXP(ANS)
      IF(PART1.LE.0.0) GOTO 965
      PART2=DIS
      ANS=(PART1+PART2)/2
  965 IF(DIS.GT.0.013) GOTO 975
      GOTO 900
  975 PART3=ANS

C HIGH EQUATION
  945 ANS=(BA(N,M)*1.382439)-(CD*0.006742263)+(DIST*0.1075394)
     1-(AD*0.003138169)-(THIN*0.09468021)-4.671048
      IF(ANS.LT.-16.118096) ANS=-16.118096
      ANS=EXP(ANS)
      IF(PART3.LE.0.0) GOTO 900
      PART4=ANS
      ANS=(PART3+PART4)/2
C CALCULATE NEW BASAL AREA AT ADDRESS 900
```

8.11 Prediction of Mortality

Two types of mortality were recognised in the trial; competition induced mortality and non-competitive mortality. The cause of non-competitive mortality was, almost invariably, wind-damage occurring in the first two years after thinning. Losses were few, only one or two trees per plot, and although such losses are in practice not without financial significance, no attempt was made to model their incidence here. (For the purposes of testing the model and comparing actual and predicted results, provision was made to 'inform' the programme which trees died from non-competitive mortality and in what year.)

Competition induced mortality was present in all unthinned plots. Such deaths occurred because competition for the essentials of plant life, sunlight, water and soil nutrients, resulted in unequal growth among competing trees followed by suppression and death of those trees least able to compete. Deaths in these plots were almost invariably the result of such suppression; disease was extremely rare, the stands being regularly sprayed with copper compounds against the common needle cast fungus Dothistroma pinii

The method of predicting death for individual trees is closely related to the calculation of increment. From examination of growth records it was observed that trees which died from competition stress were almost invariably recorded as having had no increase in diameter for some years before death. For one plot examined in detail, the average was 3.1 years (range 0-7). For the purposes of this model, death is predicted to have occurred after three years of zero increment. Because it is the logarithm of increment that is calculated, (and zero is therefore an impossible value), the method of predicting nil increment is to assign zero to all values less than a defined threshold value. The number of trees predicted

to die can be adjusted by altering this value and this was done to obtain the correct result at year 17. Once adjusted for one plot, the correct result was obtained for all plots and because of this the number of deaths can be predicted with reasonable accuracy. Results for unthinned plots in the validation set are given in Table 8.7.

Table 8.7. Actual and Predicted Mortality for Unthinned Validation Plots at 17 years

Original Plot Stocking	Actual Mortality	Predicted Mortality
318	189	188
150	37	34
129	42	46

In all three cases growth projection began at age six years. A disadvantage with this method is that, by definition, mortality cannot occur until the third year of projection. Whilst the actual and predicted number of deaths agree closely there is less agreement in identifying the actual trees which died. The percentages of trees which actually died and which were also correctly predicted as having done so are given in Table 8.8, on average this is about 65%.

Table 8.8. Individual trees Correctly Identified as dying (%)

Plot Stocking	% Correct
318	83
150	49
129	64
Mean	65

The significance of this mis-identification depends on the way in which the projected estimates are to be used. If numbers only of live or dead trees are required, the mis-identification of one third of the trees which died is of no consequence. In the total model system used here, the purpose of the diameter growth model was to provide an estimate, at a future time, of the size of each tree in the stand. In this case, where the numbers dying were predicted with reasonable accuracy, the number of trees actually dying but predicted to live was almost exactly counter-balanced by survivors which were predicted to die but which in fact lived. If the diameters of the two groups were identical no error would be involved. Unfortunately this is not the case and the two groups are not equivalent. The model tends to predict mortality amongst the smallest trees in the stand. In most cases these are indeed the trees most likely to die. Occasionally, however, deaths occur from amongst the larger trees in a stand and this is not well predicted. Since trees incorrectly predicted to survive are also predicted to grow, the net effect is to over-estimate the number of trees which will have diameters about the middle of the range for the stand and to underestimate the number of trees with diameters at the lower end of the range. The difference in size between trees incorrectly classified as dead or alive is illustrated in Table 8.9.

8.12 Validation of the Diameter Model

The validation of the diameter model is considered in two stages. The first as a model for predicting future diameter values alone, the second, as a tool to enable the prediction of stand volume by wood age. The first stage of validation is presented in this chapter and consists of a comparison of actual and predicted values for the 23 plots which comprise the validation set. All comparisons are made at 17 years of age

Table 8.9. Diameter Class Distribution Mis-identified Mortality (%)

Plot Stocking	318		150		129	
Size class (mm)	Act.Dead Pred.Dia.	Pred.Dead Act.Dia.	Act.Dead Pred.Dia.	Pred.Dead Act.Dia.	Act.Dead Pred.Dia.	Pred.Dead Act.Dia.
100	12	81		19		32
150	75	13	11	56	13	47
200	13	6	47	25	33	11
250			21		34	5
300			21		13	5
350					7	

(i.e. as at July 1980) as this is the latest data available. For over half the plots this means growth has been projected in ten or eleven annual steps. The results are given in Table 8.10.

For thinned plots the mean stand diameter was predicted with reasonable accuracy, the mean of the absolute values of the differences between actual and predicted is 3%. Three plots are predicted less well than the others; a plot thinned to 750 stems/ha with -9% difference, the plot thinned to 1350 stems/ha (-9%) and the crown thinning (-5%). In all three cases the initial diameters were smaller than might have been expected from their age alone and as the mean diameters of all were under predicted, this suggests that the model under predicts increment when smaller trees are thinned. The unthinned plots were less well predicted, in part because of the effect of mis-identified mortality. The standard deviation about the mean diameter was usually under-predicted for stockings of less than 380 stems/ha, but close to actual values for the unthinned plots or those thinned to higher stocking levels. In all cases the diameter of the largest tree in the stand was under-predicted. This was despite a routine, added

after the first comparisons were made, to boost the diameter of the largest trees in each stand. This may be because a regression based predictive method always predicts the average response to a given set of circumstances whereas in nature there is a distribution around these values. Thus the very largest and smallest values of increment would not be predicted at each annual step, resulting in the under-estimation of maximum values. Another effect of repeated annual predictions, where the predicted values of one year become the starting point for the next year's prediction, is that where values are consistently under- or over-estimated the difference between actual and predicted values will increase each time. This is true, for example, for the first plot in Table 8.10 resulting in considerable over-prediction. The danger of this happening and of obtaining an entirely false result can be lessened if more than one example of a particular regime is used as the basis of evaluation.

With the qualification that plots in which there is considerable competition induced mortality will be overestimated and that the model is unsuitable for crown thinnings, mean stand diameter is well predicted by the diameter model for the age range tested here. An average value for error obviously depends on the composition of the test sample but, excluding the crown thinning, the average error for the remaining 22 plots tested here was 4.1%. If only the mean diameter had been required, however, a stand level model would have been sufficient. The reason for developing a single tree model was to estimate the size of each tree in the stand. The effectiveness of the model in doing this is shown by deriving the frequency distribution of actual and predicted diameters and comparing them. The comparison is made in Figure 8.5. In general the distributions are similar except that in most cases the predicted distribution has a greater percentage of diameters close to the mean value

and the range is narrower than the actual range of diameters. In the majority of cases predicted distributions did not include trees in the largest of the classes actually present. The comparison of distributions reinforces the previous conclusion that the model is unsuitable for predicting growth following crown thinnings. (That is where the residual crop is not chosen from amongst the biggest trees.)

Table 8.10. Comparison of Actual and Predicted Values - Diameter at 17 years (metres)

Regime	Plot	Years Projected	Mean and Standard Deviation				% difference	Maximum Value		Minimum Value *		Mean Squared Residuals *
			Actual		Predicted			Actual	Predicted	Actual	Predicted	
T380-E	9x1	11	.399	.061	.420	.038	+5	.502	.496	.289	.319	.002390
	7x15	11	.387	.063	.388	.051	0	.514	.493	.271	.279	.001997
	6x11	11	.392	.050	.392	.042	0	.472	.468	0	.249	.004774
T380-L	7x14	11	.376	.037	.369	.039	-2	.426	.426	.293	.261	.000683
	6x10	9	.370	.054	.372	.036	+5	.469	.429	.272	.290	.001188
T380-L.R	9x3	7	.354	.054	.358	.055	+1	.450	.435	.236	.233	.000938
	7x11	8	.353	.072	.341	.058	-3	.446	.421	.155	0	.002820
	6x6	9	.363	.070	.378	.047	+4	.518	.477	0	0	.002736
T380-2	7x4	8	.375	.047	.368	.034	-2	.496	.435	.302	.279	.001028
	6x4	8	.381	.057	.377	.031	-1	.482	.431	.256	.317	.002175
	4x14	8	.365	.044	.359	.039	-2	.444	.411	0	.256	.007609
	4x19	6	.343	.051	.324	.053	-6	.442	.423	.231	.212	.001429
T500	7x10	10	.351	.064	.343	.068	-2	.474	.468	.185	.186	.001499
T750	9x9	10	.302	.067	.311	.067	+3	.439	.403	.166	0	.002593
	7x29	10	.292	.054	.285	.059	-2	.443	.390	0	0	.005097
	6x13	11	.292	.058	.310	.056	+6	.426	.384	.174	0	.003431
	4x12	11	.312	.058	.283	.065	-9	.437	.391	0	0	.005988
T1000	7x19	10	.270	.067	.282	.077	+4	.439	.393	0	0	.006712
T1350	4x16	11	.229	.050	.209	.053	-9	.356	.370	0	0	.005938
T500C	7x3	9	.344	.036	.328	.049	-5	.432	.381	.252	.229	.001953
UT2100	7x18	11	.221	.073	.246	.066	+11	.405	.380	0	0	.011964
UT3000	6x9	11	.205	.053	.229	.050	+12	.338	.330	0	0	.010079
UT5000	4x5	11	.174	.063	.173	.044	-1	.368	.337	0	0	.004981

* dead trees are assigned the value 0

Regime code: T = thinned; UT = unthinned; E = early; L = late; R = by rows; C = crown; 380 etc. = stocking in stems/ha; -2 = two thinnings.

Plot code: first numeral = original spacing in feet; second = serial number within spacing.

Figure 8.5a Comparison, Actual and Predicted Diameter Distributions

actual —— predicted - - - - -

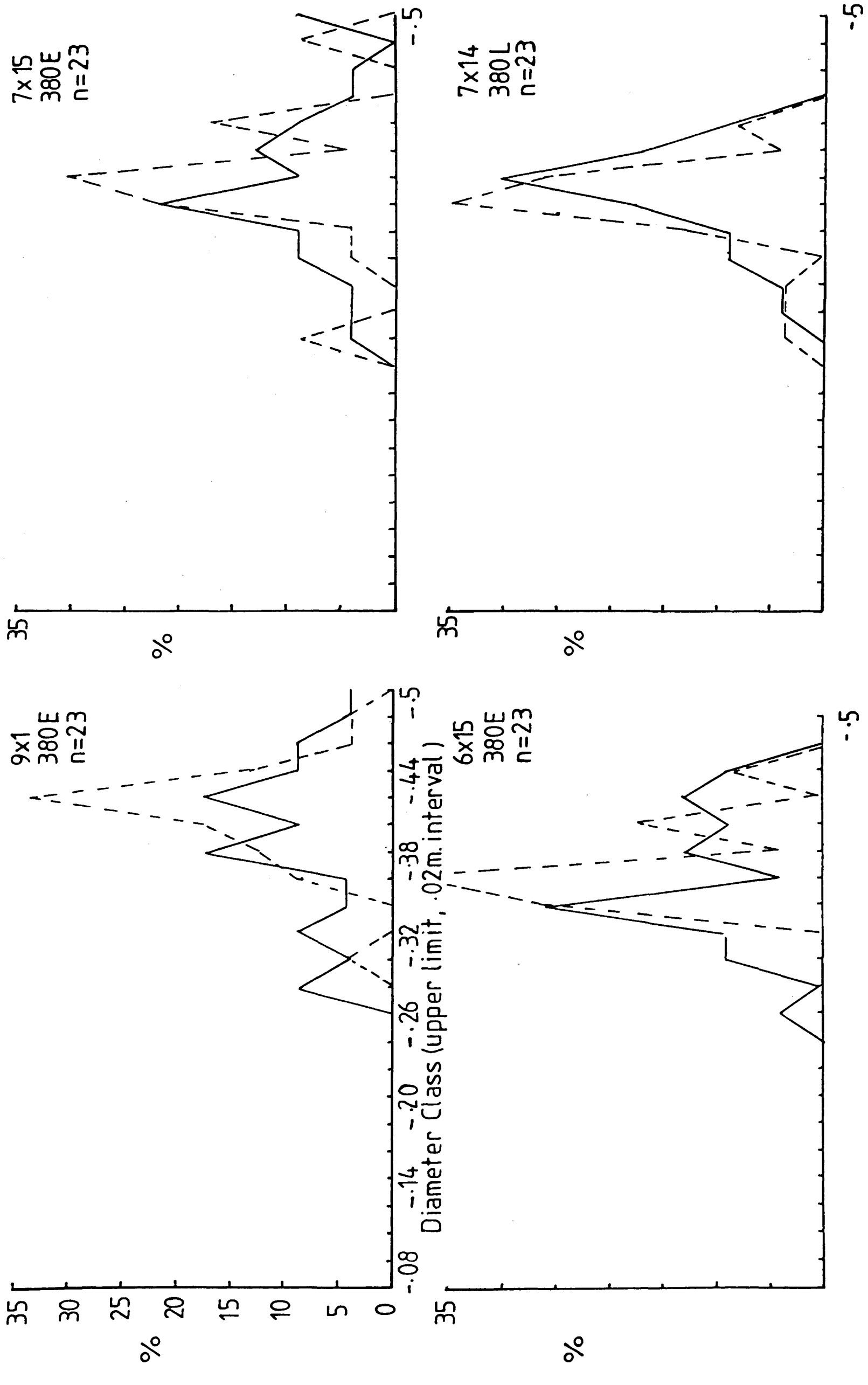
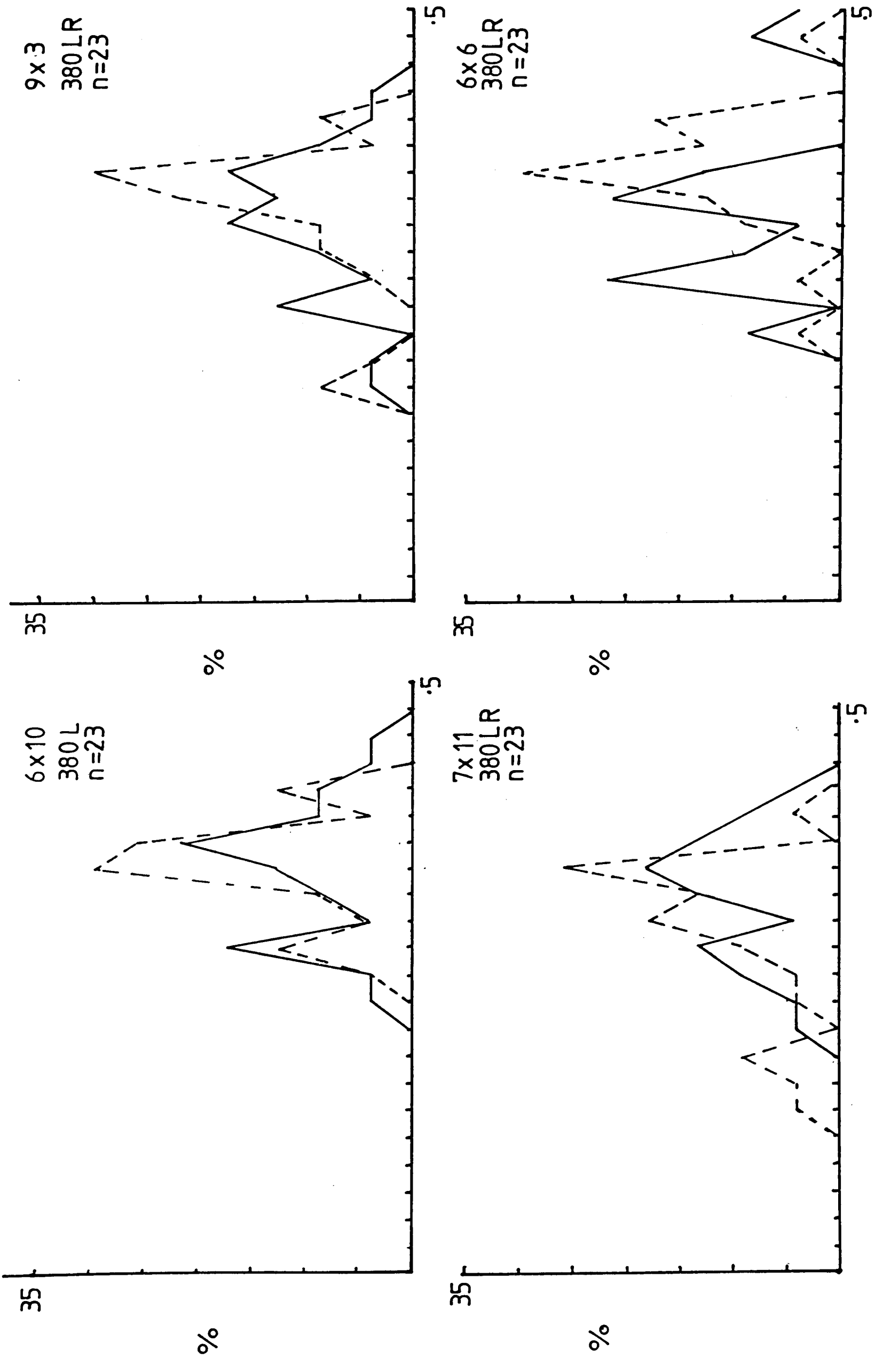
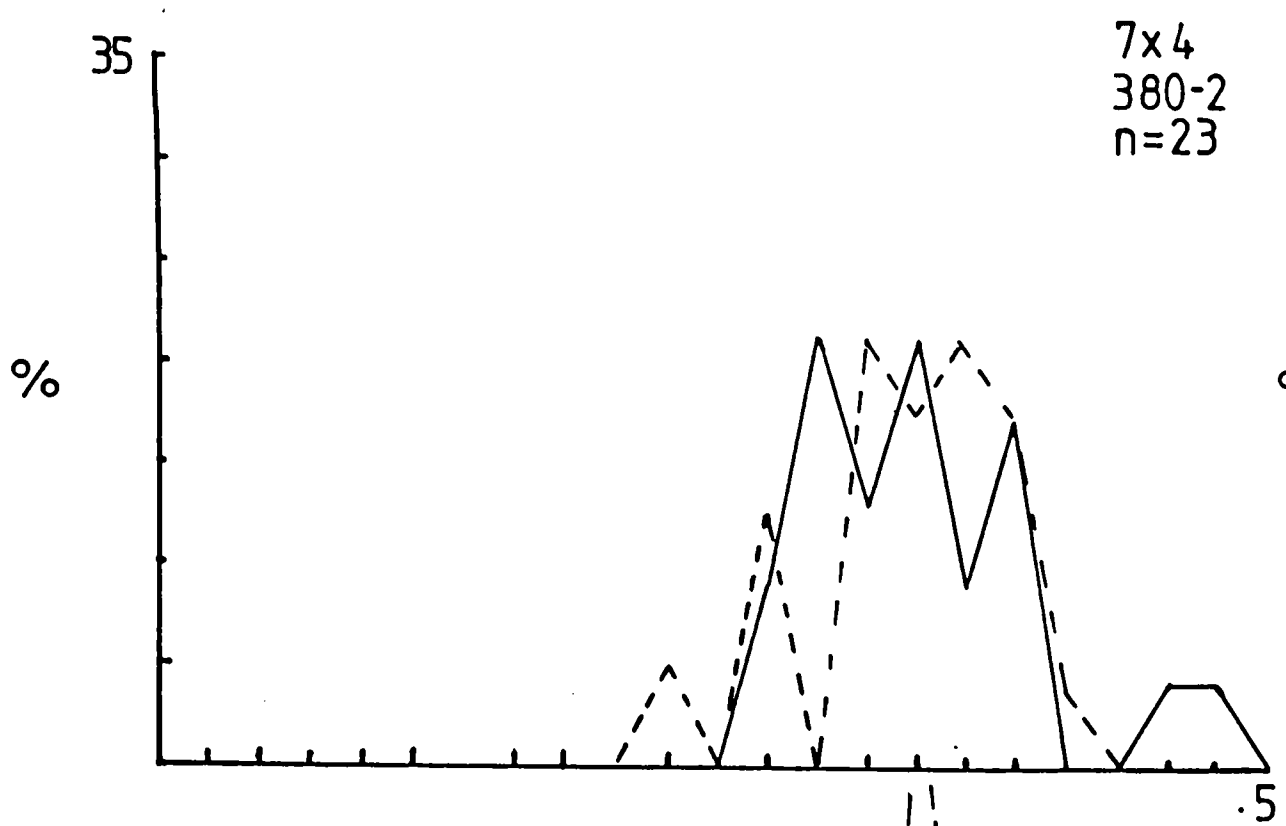
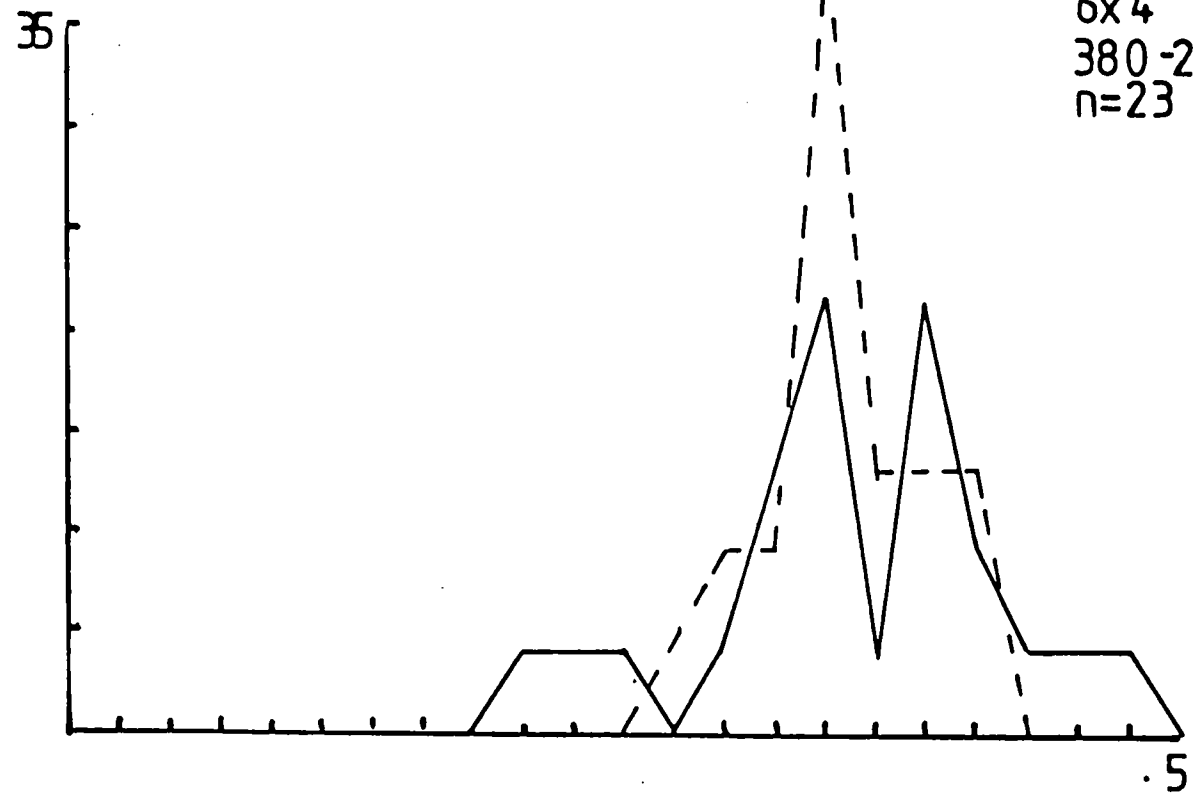
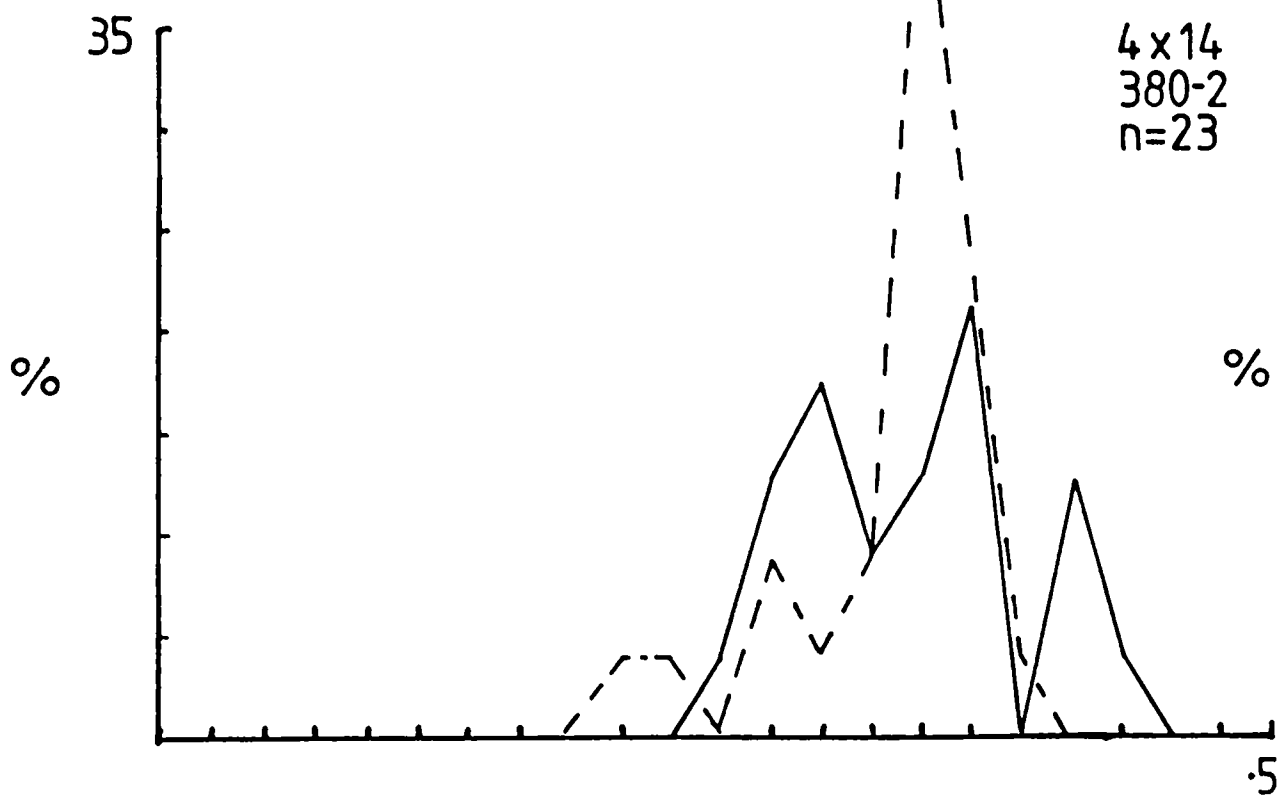


Figure 8.5 b




35
%
7x4
380-2
n=23
·5


35
%
6x4
380-2
n=23
·5


35
%
4x14
380-2
n=23
·5

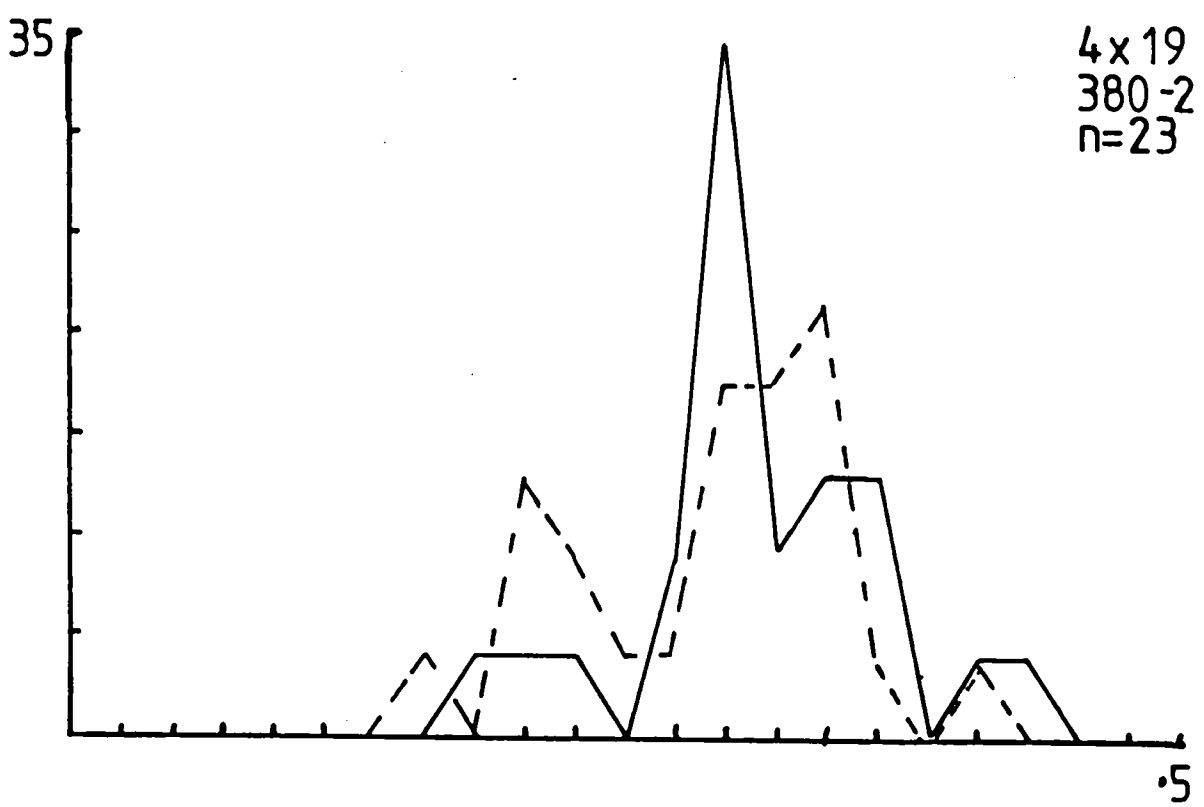

35
%
4x19
380-2
n=23
·5

Figure 8.5 c

Figure 8.5 d

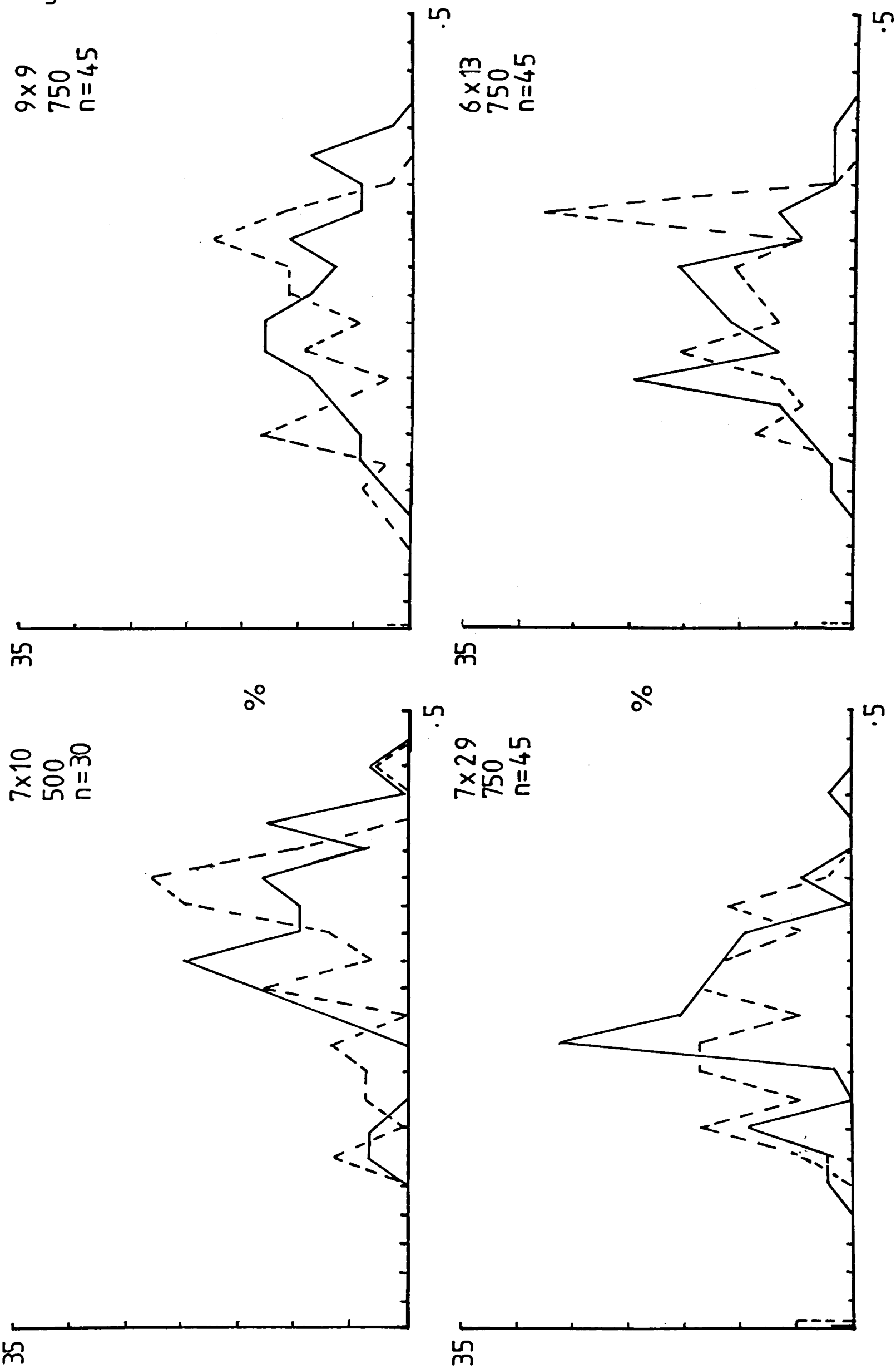


Figure 8.5 e

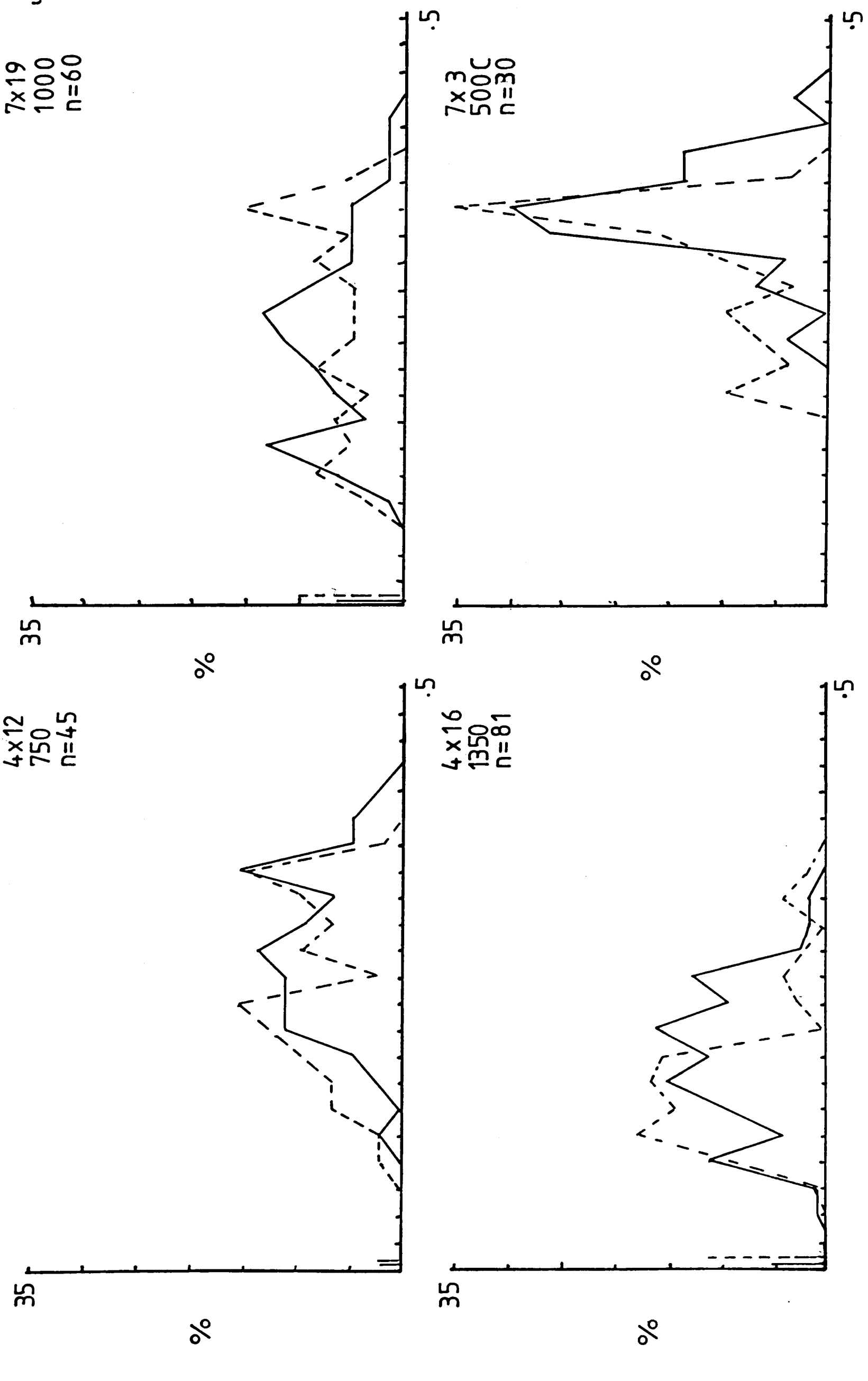
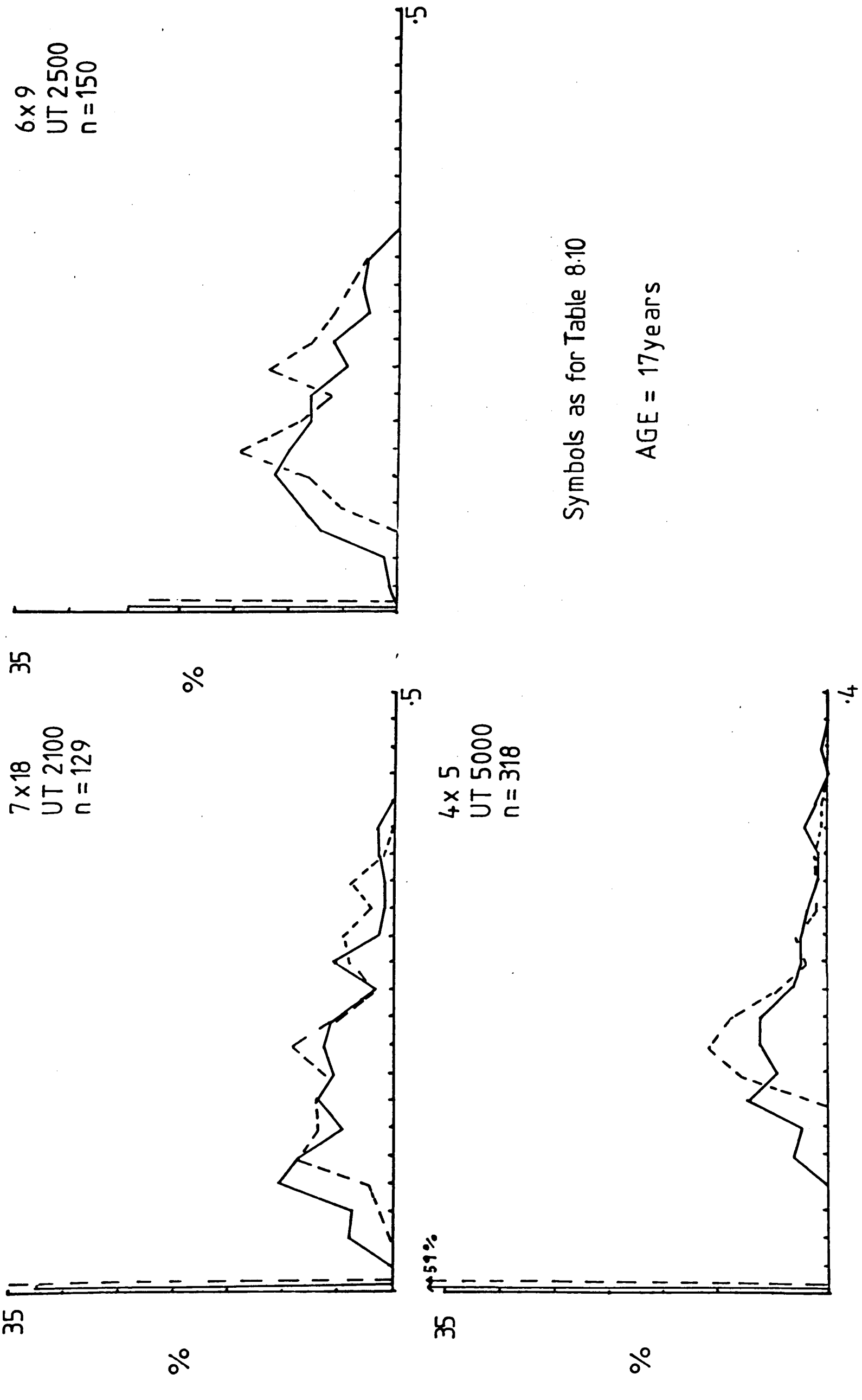


Figure 8.5 f


6 x 9
UT 2500
n = 150
.5
7 x 18
UT 2100
n = 129
35
%
.5
4 x 5
UT 5000
n = 318
59%
35
%
.4
Symbols as for Table 8.10
AGE = 17 years

CHAPTER 9

PREDICTION OF HEIGHT

9.1 Development of the Model

Two sources of information were available for the prediction of height; data from annual assessment of plots and data from felled trees. At the time of annual winter remeasurement, heights were sampled in 24 plots throughout the experiment. Six of these plots were located in each of the four stands planted at different stocking levels. Within each of these stands the heights were sampled in the three plots left as unthinned controls and in the three plots prescribed the earliest thinning to the lowest density. A total of 1,728 heights were measured during the 12 years of assessment. However, as the height parameter measured was predominant mean height, only the tallest trees in the stand were measured and therefore these data by themselves were unsuitable for constructing a model of stand height.

The other source of data was from plots where trees had been scaled for volume after felling.

In total, 17 of these plots were available, 11 of which had been clearfelled and six which had been thinned. For the thinned plots about 55 trees were measured in each plot but for the clearfelled plots the number varied between 76 and 174. The relationship between diameter and height, for a given age, has been investigated for many softwood species and many non-linear relationships have been derived, (for example Carron 1968, p.88 gives an age series for radiata pine). Accordingly, the NONLIN package was used to test whether the data conformed to these expectations. For the clearfelled plots non-linear relationships which

described 60-75% of the variation were derived. However, in the case of the thinned plots, where the trees measured were those felled during the thinning operation, the relationships had a much lower explanation of variance; commonly 30-50%. This is not surprising because the selection of crop trees was made to favour trees which were straight, of the dominant class and with a single clearly defined terminal leader. Thus most of the trees rejected under these criteria, classified as thinnings and subsequently felled and measured, would have been crooked, forked or possessing multiple leaders. All of these faults could give rise to anomalous height measurements and thus distort any derived height-diameter relationship. All data derived from thinnings were therefore rejected for the purpose of deriving a height model. The data used were derived from plots felled and measured to provide data for possible plant-and-fell regimes. Every tree in each plot was felled, d.b.h. (ob) noted and the length measured. In cases where the tree broke in falling the broken pieces were reassembled for the length measurement. The data were thus accurately derived and free of the errors often associated with height measurement of standing trees by the common trigonometrical methods.

Because every tree in the plots was measured, any trees that were malformed were also included. These trees were not segregated from the data set used to develop the height model. Although contributing to the variation, the high coefficients of determination obtained when height was regressed with diameter indicated that, in contrast to the data gathered only from thinnings, malformed trees were not present in sufficient numbers to distort the height/diameter relationship. As the model does not predict the incidence of malformation it was decided that predictions would be

more realistic if forked and crooked trees were included in the data and the variation resulting from the inclusion of all trees, quantified.

The data thus comprised a total of 1,197 trees. Although the number of trees was adequate, the distribution in time was not large, the series of clearfellings having occurred at ages 9.5 to 14.5 years inclusively. It was therefore decided to derive the model from the data from clearfelled plots but to use both the data from felling and also from annual plot assessment for validation.

When height was regressed against diameter for each of the 11 plots, many of the non-linear models tested had similar coefficients of determination. Three which most commonly gave the highest explanation of variation were:

$$y = a + be^{-cx}$$

$$y = 1/(a + be^{-cx})$$

$$y = a + b/x$$

Where y = height and x = dbh (both in metres).

In addition a multiple linear regression of height against diameter, age and transformations of these was developed. For each of the non-linear models the change with respect to time, in the value, of the coefficients was noted. For the model of the form $y = 1/(a + be^{-cx})$, the changes were not regular with time and this model was not tested. The changes of coefficient were most easily modelled for the reciprocal model $y = a + b/x$ and a short computer program was written to predict heights using this model and also for the multiple linear regression model. The results of neither were satisfactory. Although the coefficient of determination for the multiple regression was high ($r^2 = 0.8$), the model

extrapolated poorly and values for ages younger or older than the narrow data base were absurd. The reciprocal model was also unsuitable. Because the model has only two coefficients the change in shape of the height-diameter curve could not be modelled accurately with the result that for a time series the curves intersected in a manner not consistent with well established height growth trends.

The best model had the form $y = a + be^{-cx}$.

The values of the coefficients at each age are given in Table 9.1.

Table 9.1. Values of Coefficients at each age for function $y = a + be^{-cx}$

Age	Plot	Coefficient a	Coefficient b	Coefficient c
14.5	6x14	29.87852	-43.00574	9.616866
	7x14	30.26597	-38.85466	9.049361
13.5	7x13	27.79064	-39.06112	9.942641
	9x13	28.33596	-37.24559	9.161353
12.5	4x12	26.3355	-32.7815	10.60362
	6x12	25.14073	-37.78573	11.89628
11.5	9x11	22.64614	-25.83891	11.36496
	7x11	23.74714	-24.59956	8.827589
10.5	4x10	24.16769	-21.98822	3.446091
	6x10	22.99506	-26.91982	7.60244
9.5	9x9	26.10301	-20.03402	9.164456

With the exception of values for age 9.5, the coefficients a and b show a more or less regular change in value with time. Excluding age 9.5 the change in value could in both cases be described using the equation for a linear relationship. Coefficient c shows no such trend, however, the values for all ages are similar and a mean value of 9.72 can be assigned. A program was constructed which used two equations of linear form to

predict values for coefficients a and b. Coefficient c was assigned the value 9.72 and the model $y = a + be^{-cx}$ used to solve for height. When compared with actual values, the shape of the curve seemed to be described accurately but the level was often wrong. Use of the model in this form, with coefficient a predicted by a straight line equation implies a constant rate of increase in height at all ages - clearly an unrealistic growth pattern in biological terms. By comparing actual and predicted values a correction factor, based on an equation of quadratic form was applied to coefficient a. This adjustment markedly improved the fit. In the case of small tree diameters where trees were over 14 years old the values were anomalous; this was simply an artifact of the method of calculation and such values were constrained so that heights did not decrease with increasing age. Values of height from age 6 to age 20 and from diameter 0.1m to 0.475m are given in Table 9.2. The program, in FORTRAN, which was used to produce Table 9.2 is given below.

9.2 Validation of the Height Model

The height model was validated by graphical comparison between actual and predicted values. Every second year was considered, starting with age 6. For the ages 6, 8 and 16, data from annual assessment were used, for the other ages a systematic sample of the original data was used. Of the 24 plots for which height data were collected by annual measurement, eight plots, one from each regime selected at random, were used. This gave a total of 48 trees per year. For ages 10, 12 and 14, 20 trees per clearfelled plot were selected or 40 trees per year. The graphs are given as Figure 9.1 and in each of the five cases show that the predicted height passes through the centre of the distributed values. The graphs also illustrate the considerable variation in actual height

```
      PROGRAM HEIGHTMOD
C PREDICTS HT FROM D.B.H. & HGT
      INTEGER AGE
      DIMENSION HT(20),TITLE(20)
      WRITE(2,100)
  100 FORMAT(1H1,//,45X,'HEIGHT PREDICTED FROM D.B.H. & AGE ')
      WRITE(2,40)
   40 FORMAT(1H ,50X,'DIAMETER (B.H.,O.B.)')
      WRITE(2,50)
   50 FORMAT(1H ,/,6X,'AGE  !')
      TITLE(1)=0.100
      DO 60 K=2,16
      TITLE(K)=TITLE(K-1)+0.025
   60 CONTINUE
      WRITE(2,70)(TITLE(L),L=1,16)
   70 FORMAT(1H+,12X,16F7.3)
      DO 10 AGE=6,20
      COFA=3.325557+(AGE*1.836691)
      CRTA=9.849823-(AGE*1.549468)+((AGE**2)*0.06715343)
      CRTA=CRTA-1
      COFA=COFA-CRTA
      COFB=-1*(AGE*4.588648-24.55002)
      COFC=9.72
      DBH=0.075
      DO 20 I=1,16
      DBH=DBH+0.025
      HT(I)=COFA+COFB*EXP(-COFC*DBH)
      IF(AGE.GT.13) HT(1)=13.87
      IF(AGE.GT.15) HT(2)=17.02
      IF(AGE.GT.17) HT(3)=20.19
      IF(AGE.GT.19) HT(4)=23.14
   20 CONTINUE
      WRITE(2,30)AGE,(HT(I),I=1,16)
   30 FORMAT(1H ,/,5X,I4,2X,'!',16F7.2,/)
   10 CONTINUE
      STOP
      END
```

Table 92

HEIGHT PREDICTED FROM D.B.H. & AGE
DIAMETER (B.H./O.B.)

AGE	0.100	0.125	0.150	0.175	0.200	0.225	0.250	0.275	0.300	0.325	0.350	0.375	0.400	0.425	0.450	0.475
6	11.25	11.49	11.68	11.83	11.95	12.04	12.11	12.17	12.21	12.25	12.28	12.30	12.31	12.33	12.34	12.35
7	12.02	12.64	13.13	13.51	13.80	14.04	14.22	14.37	14.48	14.57	14.64	14.69	14.73	14.77	14.79	14.81
8	12.67	13.66	14.44	15.05	15.53	15.90	16.20	16.43	16.61	16.75	16.86	16.95	17.02	17.07	17.11	17.15
9	13.18	14.54	15.51	16.46	17.11	17.63	18.04	18.36	18.60	18.80	18.95	19.07	19.17	19.24	19.30	19.35
10	13.55	15.29	16.66	17.73	18.57	19.23	19.74	20.15	20.47	20.72	20.91	21.06	21.18	21.28	21.35	21.41
11	13.79	15.91	17.57	18.87	19.89	20.69	21.32	21.81	22.19	22.50	22.73	22.92	23.07	23.18	23.27	23.34
12	13.90	16.39	18.34	19.87	21.07	22.01	22.75	23.33	23.79	24.14	24.42	24.64	24.81	24.95	25.06	25.14
13	13.97	16.73	18.98	20.74	22.12	23.21	24.06	24.72	25.25	25.66	25.98	26.23	26.43	26.58	26.70	26.80
14	13.97	16.94	19.48	21.48	23.04	24.26	25.23	25.98	26.57	27.03	27.40	27.68	27.91	28.08	28.22	28.33
15	13.97	17.02	19.85	22.08	23.82	25.19	26.20	27.10	27.76	28.28	28.68	29.00	29.25	29.45	29.60	29.72
16	13.97	17.02	20.09	22.54	24.47	25.98	27.16	28.09	28.82	29.39	29.84	30.19	30.46	30.68	30.85	30.98
17	13.97	17.02	20.19	22.88	24.98	26.63	27.93	28.94	29.74	30.36	30.85	31.24	31.54	31.77	31.96	32.10
18	13.97	17.02	20.19	23.08	25.36	27.15	28.56	29.66	30.53	31.20	31.74	32.15	32.48	32.74	32.94	33.10
19	13.97	17.02	20.19	23.14	25.61	27.54	29.06	30.25	31.18	31.91	32.48	32.93	33.29	33.56	33.78	33.95
20	13.97	17.02	20.19	23.14	25.72	27.79	29.42	30.70	31.70	32.48	33.10	33.58	33.96	34.26	34.49	34.67

Figure 9.1 Comparison of Predicted Height & Actual Data

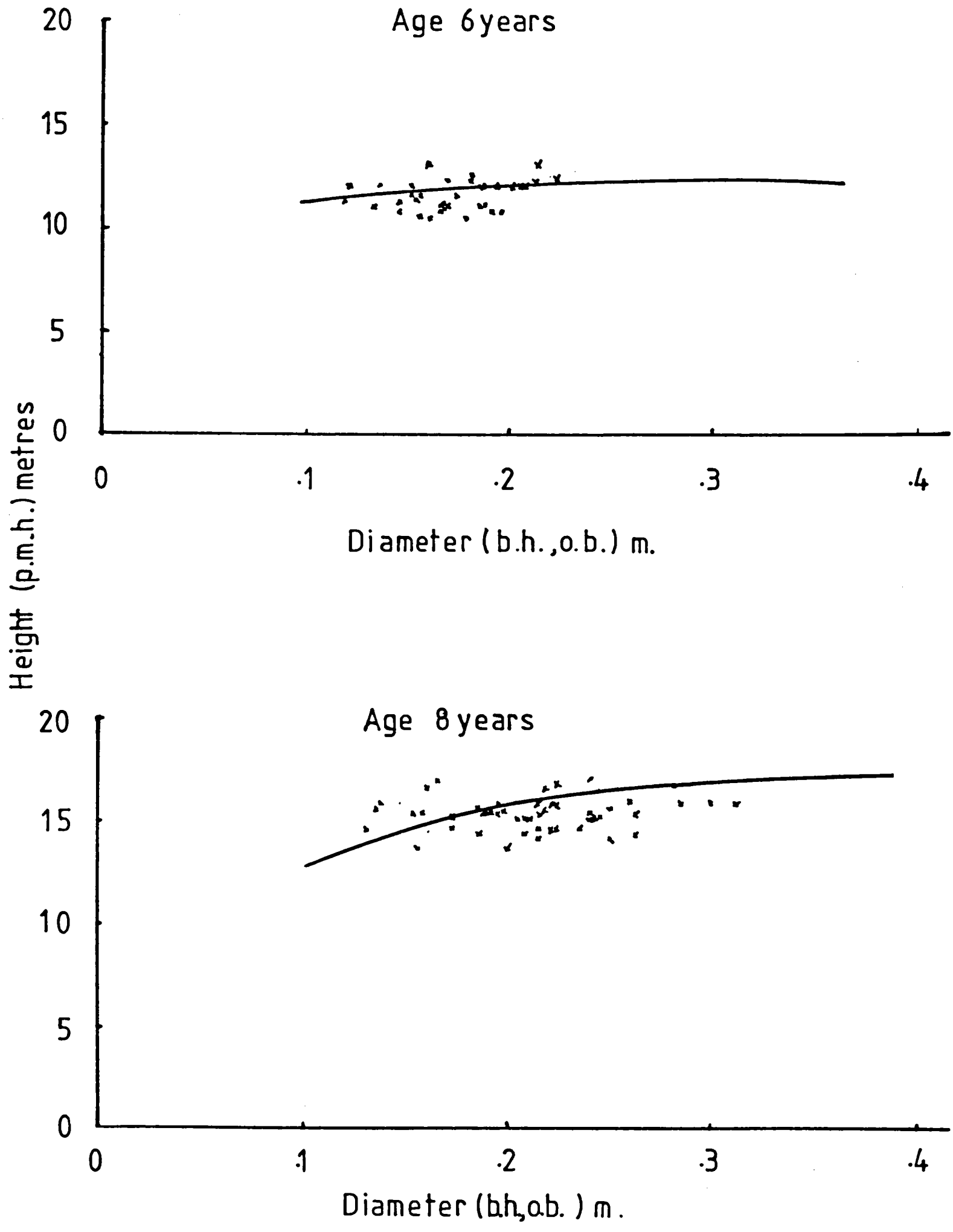


Figure 9.1 b

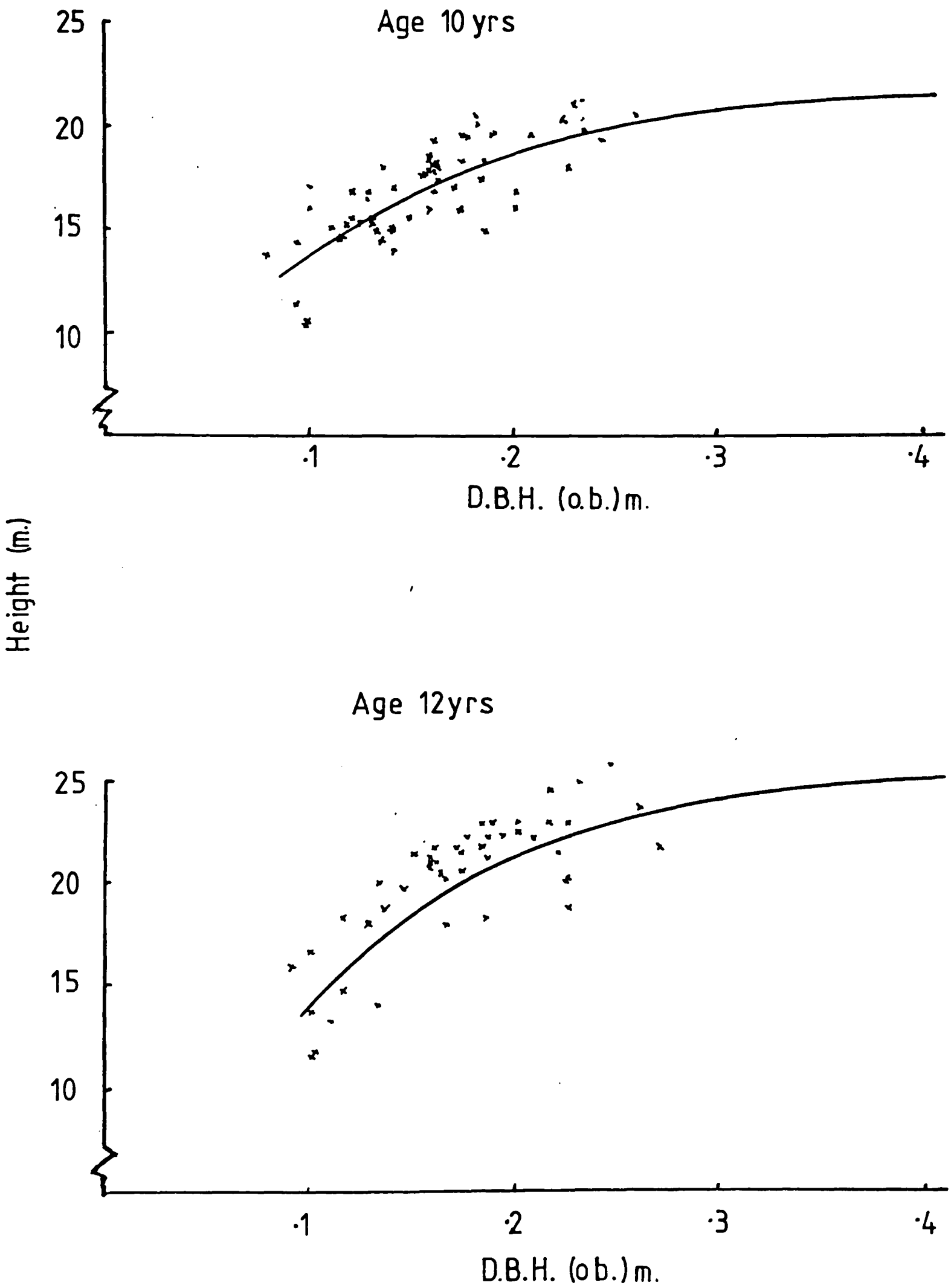
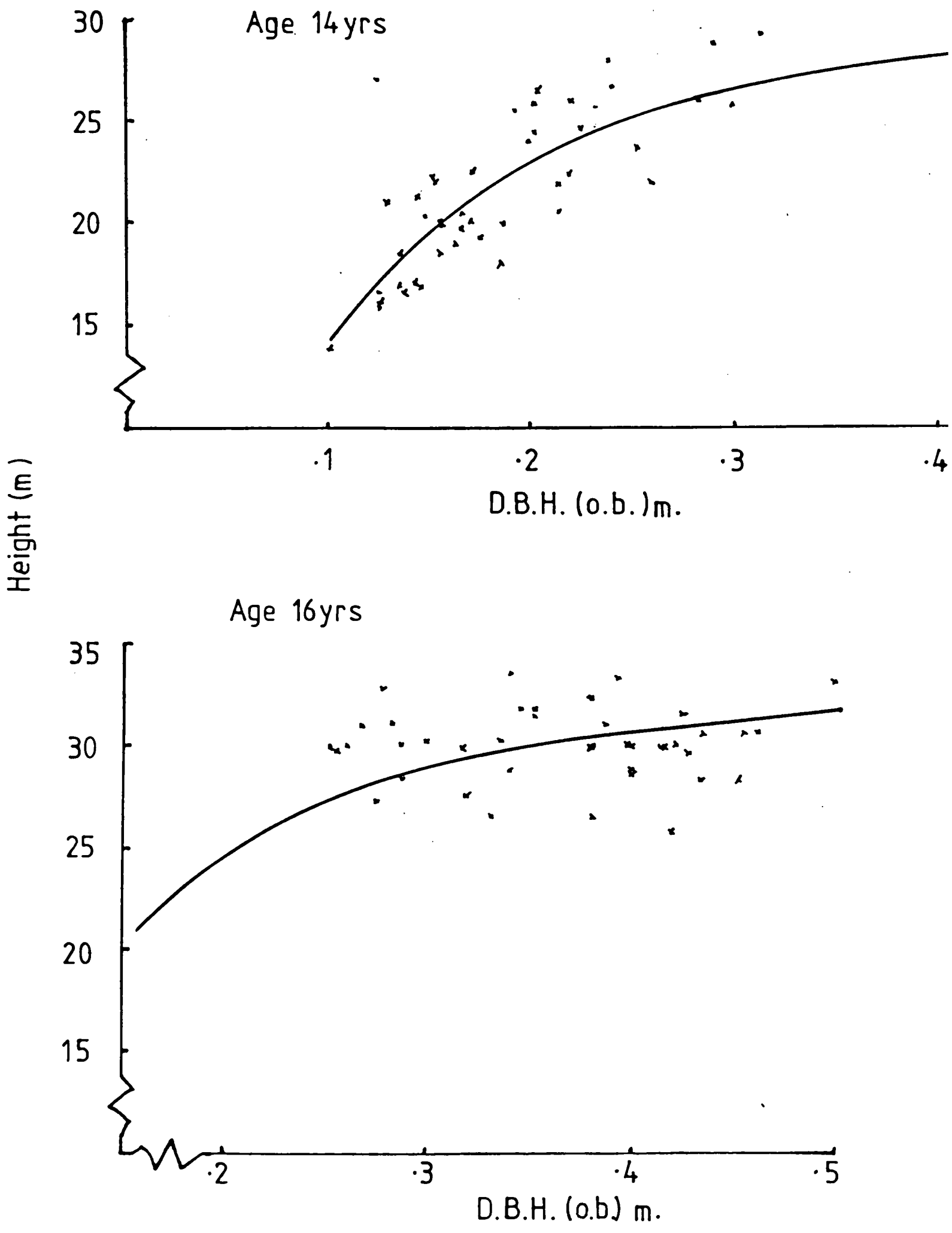

Age 10 yrs
25
20
15
10
·1
·2
·3
·4
D.B.H. (o.b.)m.
Height (m.)
Age 12yrs
25
20
15
10
·1
·2
·3
·4
D.B.H. (o.b.)m.

Figure 9.1c


Age 14yrs
30
25
20
15
·1
·2
·3
·4
D.B.H. (o.b.)m.
Height (m)
Age 16yrs
35
30
25
20
15
·2
·3
·4
·5
D.B.H. (o.b) m.

for diameter. To take account of this and to avoid the unrealistic situation where for every combination of diameter and age only one height would be predicted, stochastic variation in predicted height was allowed. To calculate this, the limits of the data were sketched on the graphs, then quantified. Although the difference from the mean that was needed to cover the range of data increased with age, the percentage difference was less variable. Over the range of ages 6-16 years, the average difference of ±14% from the mean covered almost all the spread of data. This value was treated as three standard deviations. By using the appropriate routines from the Numerical Algorithm library, new values for height were assigned by a random number generator where values were constrained to a normal distribution with a mean equal to the original predicted value and with a shape determined by the derived value of the standard deviation. An example of the stochastic variation in the magnitude of predicted height is given in Table 9.3. Because predicted height is used as an independent variable in the calculation of volume and wood age the variation introduced here causes variation in those values also. On a stand basis this is realistic.

Table 9.3 Height Predicted from D.B.H. and Age, with Stochastic Variation

HEIGHT PREDICTED FROM D.B.H. & AGE
DIAMETER (B.H.,O.B.)

AGE	0.100	0.125	0.150	0.175	0.200	0.225	0.250	0.275	0.300	0.325	0.350	0.375	0.400	0.425	0.450	0.475
6	11.25	11.49	11.68	11.83	11.95	12.04	12.11	12.17	12.21	12.25	12.28	12.30	12.31	12.33	12.34	12.35
	11.53	12.18	12.54	11.82	12.79	11.80	11.68	12.30	12.33	11.42	12.31	13.18	13.89	12.68	12.00	12.25
	11.98	11.03	11.90	12.01	12.00	11.39	12.72	12.53	12.03	13.48	12.49	12.54	12.59	12.49	12.54	13.23
	11.43	10.98	11.70	12.71	11.25	11.35	12.22	11.29	12.50	12.45	12.35	11.40	12.26	11.56	12.26	11.82
	11.05	12.24	11.94	11.52	12.47	11.07	14.13	12.79	11.67	11.93	13.80	12.34	12.05	11.65	12.90	12.18
	11.33	10.72	11.03	11.27	11.55	12.48	11.72	12.54	12.65	11.45	11.71	12.57	12.86	12.40	13.06	12.99
	9.98	11.52	11.51	11.58	12.21	12.59	12.67	12.45	12.84	12.12	12.12	12.40	12.90	12.33	12.86	12.23
	11.78	12.11	12.00	12.63	11.81	11.30	12.71	11.61	11.88	11.87	13.08	12.72	12.91	11.79	12.00	11.43
	11.62	11.56	11.25	11.81	11.61	11.25	11.17	12.27	12.23	11.39	12.74	12.04	12.76	12.74	12.84	12.45
	11.02	10.51	11.92	11.58	10.84	13.05	12.52	12.08	11.64	11.82	11.11	12.18	12.47	12.74	11.33	11.15
	11.56	10.47	12.08	11.52	11.63	11.78	11.55	11.37	11.83	12.30	12.28	12.44	11.89	12.08	12.64	11.38
7	12.02	12.64	13.13	13.51	13.80	14.04	14.22	14.37	14.48	14.57	14.64	14.69	14.73	14.77	14.79	14.81
	12.33	13.40	14.09	13.49	14.78	13.76	13.71	14.52	14.62	13.58	14.68	15.75	16.62	15.19	14.39	14.70
	12.81	12.13	13.38	13.71	13.86	13.28	14.93	14.79	14.26	16.04	14.90	14.98	15.06	14.96	15.03	15.27
	12.22	12.08	13.15	14.51	13.00	13.24	14.34	13.33	14.82	14.81	14.73	13.62	14.67	13.84	14.69	14.79
	11.82	13.46	13.42	13.15	14.41	12.90	16.59	15.09	13.83	14.19	16.45	14.74	14.42	13.95	15.47	14.61
	12.11	11.79	12.39	12.87	13.34	14.55	13.76	14.80	14.99	13.62	13.96	15.01	15.39	14.85	15.66	15.58
	10.67	12.67	12.93	13.22	14.11	14.68	14.87	14.70	15.22	14.41	14.45	14.81	15.44	14.77	15.42	14.68
	12.59	13.32	13.49	14.42	13.65	13.18	14.92	13.71	14.08	14.11	15.59	15.19	15.44	14.12	14.39	13.72
	12.42	12.72	12.65	13.48	13.41	13.11	13.11	14.48	14.50	13.55	15.18	14.39	15.27	15.26	15.39	14.94
	11.78	11.57	13.40	13.22	12.52	15.21	14.70	14.27	13.79	14.06	13.25	14.55	14.91	15.26	13.59	13.36
	12.36	11.52	13.58	13.15	13.44	13.74	13.56	13.42	14.02	14.63	14.64	14.87	14.23	14.47	15.16	13.60
8	12.67	13.66	14.44	15.05	15.53	15.90	16.20	16.43	16.61	16.75	16.86	16.95	17.02	17.07	17.11	17.15
	12.98	14.48	15.50	15.03	16.63	15.58	15.61	16.61	16.77	15.62	16.91	18.17	19.20	17.55	16.64	17.02
	13.49	13.11	14.71	15.28	15.59	15.04	17.00	16.91	16.35	18.44	17.16	17.28	17.40	17.29	17.39	18.37
	12.87	13.05	14.46	16.17	14.62	15.00	16.34	15.24	17.00	17.03	16.97	15.72	16.94	16.01	17.00	16.42
	12.45	14.55	14.76	14.65	16.21	14.61	18.89	17.26	15.87	16.32	18.95	17.00	16.66	16.13	17.89	15.92
	12.76	12.74	13.63	14.33	15.01	16.49	15.67	16.93	17.20	15.66	16.09	17.32	17.77	17.17	18.11	18.04
	11.24	13.69	14.22	14.73	15.87	16.63	16.94	16.81	17.46	16.57	16.65	17.09	17.83	17.08	17.84	16.99
	13.26	14.39	14.84	16.06	15.35	14.93	16.99	15.68	16.15	16.23	17.96	17.53	17.84	16.32	16.64	15.88
	13.08	13.74	13.91	15.02	15.09	14.85	14.93	16.56	16.63	15.58	17.49	16.60	17.64	17.65	17.81	17.30
	12.41	12.50	14.74	14.73	14.08	17.23	16.74	16.31	15.82	16.17	15.26	16.79	17.23	17.65	15.72	15.49
	13.02	12.45	14.93	14.65	15.12	15.56	15.45	15.35	16.09	16.82	16.87	17.15	16.44	16.73	17.54	15.74
9	13.18	14.54	15.61	16.46	17.11	17.63	18.04	18.36	18.60	18.80	18.95	19.07	19.17	19.24	19.30	19.35
	13.51	15.42	16.77	16.43	18.33	17.28	17.39	18.56	18.78	17.53	19.01	20.45	21.63	19.79	18.77	19.20
	14.03	13.96	15.91	16.71	17.19	16.68	18.93	18.89	18.32	20.70	19.29	19.45	19.60	19.49	19.61	20.23
	13.39	13.90	15.64	17.68	16.11	16.63	18.19	17.03	19.04	19.11	19.08	17.69	19.08	18.04	19.17	18.53
	12.95	15.49	15.96	16.02	17.86	16.20	21.04	19.28	17.78	18.32	21.31	19.14	18.76	18.18	20.18	19.09
	13.27	13.57	14.74	15.67	16.54	18.28	17.45	18.91	19.26	17.57	18.08	19.49	20.02	19.36	20.43	20.36
	11.70	14.58	15.38	16.11	17.49	18.44	18.86	18.78	19.56	18.60	18.72	19.23	20.08	19.25	20.12	19.17
	13.79	15.32	16.05	17.56	16.92	16.55	18.92	17.52	18.09	18.22	20.19	19.73	20.09	18.40	18.77	17.92
	13.61	14.63	15.04	16.43	16.63	16.47	16.63	18.50	18.63	17.48	19.66	18.68	19.87	19.89	20.08	19.52
	12.91	13.30	15.94	16.10	15.52	19.11	18.64	18.23	17.73	18.14	17.16	18.89	19.40	19.89	17.73	17.48
	13.54	13.25	16.15	16.02	16.66	17.25	17.20	17.15	18.02	18.88	18.96	19.30	18.51	18.86	19.78	17.76

CHAPTER 10

PREDICTION OF TREE VOLUME

The data on which the volume model is based is essentially the same as that for the height model. That is from the series of plots clearfelled to determine volume. The number of trees available is not exactly the same because for one plot only height and diameter data were available but another plot with only a few, large trees was added. The total number of trees was 1,004 and these were distributed in size as indicated in Table 10.1.

The method of field measurement was to mark and measure breast height, fell the tree and measure its length, then measure stem diameters. As the data were initially required for the estimation of volumes, for a pulping process where wood is used in 4ft (1.2m) billet lengths; this was adopted at the measurement interval. Outside bark diameter and bark thickness was measured every 1.2 metres beginning at the butt until the diameter inside bark was less than 10cm. Where the 1.2m interval coincided with a nodal swelling, measurements were taken at equal distances above and below the node. Volumes, inside bark, to a 10cm top were calculated by summing the volume of each 1.2m billet; the volume of each billet being calculated by Smalian's formula.

To develop the volume model the Oxford Forestry Department package VOLTAB was used. This package uses combinations of diameter, height and transformations of these variables to test 15 possible models to derive volume or a transformation of volume. The 'best' model is chosen using the Furnival index (Furnival 1961) as the criterion of choice. For these data the equation with the lowest Furnival index was of the form

Table 10.1. Distribution of Volume Data

Diameter (m)	Height class (metres)											
	11.0	13.0	15.0	17.0	19.0	21.0	23.0	25.0	27.0	29.0	31.0	33.0 Total
0 - .02												
- .04												
- .06												
- .08	1	1										2
- .1	8	11	11	4								34
- .12	7	12	49	23	2							93
- .14	6	13	37	31	23	5	1					116
- .16	3	4	19	47	39	21	4	2				139
- .18		3	17	32	46	49	20	1				168
- .2		1	5	20	33	37	22	14	2			134
- .22	1	0	5	13	16	23	37	11	4			110
- .24	1	0	1	12	8	17	18	12	7			76
- .26				3	2	11	9	21	6			52
- .28					2	11	6	11	7	1	1	39
- .30						2	1	6	4	1		14
- .32							2	2	5	3		12
- .34								2				2
- .36									1	1		2
- .38												
- .40												
- .42										4	0	1 5
- .44										1	1	1 3
- .46									1			1
- .48											1	1
- .50												1 1
	27	45	144	185	171	176	120	82	37	11	3	3 1004

$$\text{Ln Vol} = \text{Ln DBH} + \text{Ln HT}$$

(Where Vol = volume, DBH = diameter at breast height and HT = height, and Ln indicates the natural logarithm.)

$r^2 = 0.9156$ Furnival Index* = 0.0414475

This equation, however, gave absurd results, greatly exaggerating the size of the larger trees. Other equations were examined (in order of ascending Furnival index) until a model was found which resulted in predicted values which closely conformed to actual values. This was of the form

$$\text{Volume} = (\text{DBH})^2 \times \text{HT} + \text{constant}$$

$r^2 = 0.828$ Furnival Index = 0.0982667

The derived volume table and confidence limits at 95% probability are given in Table 10.2. For the largest class of trees these confidence limits represent ±2.7% of the volume; the model can thus be said to predict volume closely.

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* The Furnival Index is a method of comparing equations where the variables are transformed or weighted and thus where the equations cannot be evaluated by comparing r^2. The index is based on maximum likelihood as this 'reflects both the size of the residuals and possible departure from linearity, normality and homoscedasity'. The general form of the index of fit is: Index = $[F'(V)]^{-1}S$, where $F'(V)$ is the first derivative of the independent variable with respect to volume and S is the root mean square of the residuals of the equation to be compared.

MODEL 4 V = DDH

****
* BEST FIT *
****

VARIABLES 1 ON 11 ,

ANALYSIS OF VARIANCE

DUE TO	DF	SS	MS	F
REGRESSION	1	4.68900E+01	4.68900E+01	4855.87
RESIDUAL	1002	9.67566E+00	9.65635E-03	
TOTAL	1003	5.65657E+01		

RR 0.82895 R 0.91047 SD 9.82667E-02 SD0/0 46.256

VARIABLE	MEAN	BETA	B	VARIANCE	SE	T
1(11)	7.62827E-01	0.91047	2.91751E-01	1.75290E-05	4.18677E-03	69.684

CONSTANT -1.01147E-02

FURNIVAL INDEX 9.82667E-02

VOLUME TABLE MODEL 4 V = ODH

PINUS RADIATA TARAWERA VOLUME TO 10CM FOR DIAMETER(M) & TOTAL HEIGHT(M)

	HEIGHT										
DIAMETER	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0
0.05	-0.003	-0.002	-0.001	-0.001	0.000	0.001	0.002	0.002	0.003	0.004	0.004	0.005
0.06	0.000	0.001	0.002	0.004	0.005	0.006	0.007	0.008	0.009	0.010	0.011	0.012
0.07	0.004	0.006	0.007	0.008	0.010	0.011	0.013	0.014	0.016	0.017	0.018	0.020
0.08	0.009	0.010	0.012	0.014	0.016	0.018	0.020	0.022	0.023	0.025	0.027	0.029
0.09	0.014	0.016	0.018	0.021	0.023	0.025	0.028	0.030	0.032	0.035	0.037	0.040
0.10	0.019	0.022	0.025	0.028	0.031	0.034	0.037	0.039	0.042	0.045	0.048	0.051
0.11	0.025	0.029	0.032	0.036	0.039	0.043	0.046	0.050	0.053	0.057	0.060	0.064
0.12	0.032	0.036	0.040	0.045	0.049	0.053	0.057	0.061	0.066	0.070	0.074	0.078
0.13	0.039	0.044	0.049	0.054	0.059	0.064	0.069	0.074	0.079	0.084	0.088	0.093
0.14	0.047	0.053	0.059	0.064	0.070	0.076	0.081	0.087	0.093	0.099	0.104	0.110
0.15	0.056	0.062	0.069	0.075	0.082	0.088	0.095	0.101	0.108	0.115	0.121	0.128
0.16	0.065	0.072	0.080	0.087	0.094	0.102	0.109	0.117	0.124	0.132	0.139	0.147
0.17	0.074	0.083	0.091	0.099	0.108	0.116	0.125	0.133	0.142	0.150	0.159	0.167
0.18	0.084	0.094	0.103	0.113	0.122	0.132	0.141	0.151	0.160	0.169	0.179	0.188
0.19	0.095	0.106	0.116	0.127	0.137	0.148	0.158	0.169	0.179	0.190	0.201	0.211
0.20	0.107	0.118	0.130	0.142	0.153	0.165	0.177	0.188	0.200	0.212	0.223	0.235
0.21	0.119	0.131	0.144	0.157	0.170	0.183	0.196	0.209	0.221	0.234	0.247	0.260
0.22	0.131	0.145	0.159	0.173	0.188	0.202	0.216	0.230	0.244	0.258	0.272	0.286
0.23	0.144	0.160	0.175	0.191	0.206	0.221	0.237	0.252	0.268	0.283	0.299	0.314
0.24	0.158	0.175	0.192	0.208	0.225	0.242	0.259	0.276	0.292	0.309	0.326	0.343
0.25	0.172	0.190	0.209	0.227	0.245	0.263	0.282	0.300	0.318	0.336	0.355	0.373
0.26	0.187	0.207	0.227	0.246	0.266	0.286	0.305	0.325	0.345	0.365	0.384	0.404
0.27	0.203	0.224	0.245	0.266	0.288	0.309	0.330	0.351	0.373	0.394	0.415	0.437
0.28	0.219	0.241	0.264	0.287	0.310	0.333	0.356	0.379	0.402	0.424	0.447	0.470
0.29	0.235	0.260	0.284	0.309	0.333	0.358	0.382	0.407	0.432	0.456	0.481	0.505
0.30	0.252	0.279	0.305	0.331	0.357	0.384	0.410	0.436	0.463	0.489	0.515	0.541
0.31	0.270	0.298	0.326	0.354	0.382	0.410	0.438	0.467	0.495	0.523	0.551	0.579
0.32	0.289	0.319	0.348	0.378	0.408	0.438	0.468	0.498	0.528	0.558	0.587	0.617
0.33	0.308	0.339	0.371	0.403	0.435	0.466	0.498	0.530	0.562	0.594	0.625	0.657
0.34	0.327	0.361	0.395	0.428	0.462	0.496	0.530	0.563	0.597	0.631	0.664	0.698
0.35	0.347	0.383	0.419	0.454	0.490	0.526	0.562	0.597	0.633	0.669	0.705	0.740
0.36	0.368	0.406	0.444	0.481	0.519	0.557	0.595	0.633	0.670	0.708	0.746	0.784
0.37	0.389	0.429	0.469	0.509	0.549	0.589	0.629	0.669	0.709	0.749	0.789	0.829
0.38	0.411	0.453	0.495	0.538	0.580	0.622	0.664	0.706	0.748	0.790	0.832	0.875
0.39	0.434	0.478	0.522	0.567	0.611	0.656	0.700	0.744	0.789	0.833	0.877	0.922

CONFIDENCE LIMITS(95%)

0.05	-0.012	-0.011	-0.010	-0.009	-0.009	-0.008	-0.007	-0.006	-0.006	-0.005	-0.004	-0.003
	0.006	0.007	0.007	0.008	0.009	0.010	0.010	0.011	0.012	0.012	0.013	0.014
0.10	0.011	0.014	0.017	0.020	0.023	0.026	0.029	0.032	0.035	0.037	0.040	0.043
	0.027	0.030	0.033	0.036	0.039	0.042	0.045	0.047	0.050	0.053	0.056	0.059
0.15	0.048	0.055	0.061	0.068	0.075	0.081	0.088	0.095	0.101	0.108	0.114	0.121

Table 10.2

							-0.003		
							0.014		
							0.043		
							0.059		
							0.121		
							0.134		
							0.229		
							0.241		
							0.365		
							0.381		
							0.530		
							0.553		
							0.724		
							0.757		
						-0.004			
						0.013			
						0.040			
						0.056			
						0.114			
						0.128			
						0.217			
						0.229			
						0.347			
						0.362			
						0.504			
						0.526			
						0.689			
						0.720			

CONFIDENCE LIMITS(95%)

0.05	-0.012	-0.011	-0.010	-0.009	-0.009	-0.008	-0.007	-0.006	-0.005
	0.006	0.007	0.007	0.008	0.009	0.010	0.010	0.012	0.012
0.10	0.011	0.014	0.017	0.020	0.023	0.026	0.029	0.032	0.037
	0.027	0.030	0.033	0.036	0.039	0.042	0.045	0.047	0.053
0.15	0.048	0.055	0.061	0.068	0.075	0.081	0.088	0.095	0.108
	0.063	0.070	0.076	0.083	0.089	0.096	0.102	0.108	0.121
0.20	0.100	0.111	0.123	0.135	0.147	0.159	0.170	0.182	0.205
	0.113	0.125	0.137	0.148	0.160	0.171	0.183	0.195	0.218
0.25	0.166	0.184	0.202	0.221	0.239	0.257	0.275	0.293	0.329
	0.179	0.197	0.215	0.233	0.251	0.270	0.288	0.307	0.343
0.30	0.246	0.272	0.298	0.324	0.350	0.376	0.402	0.427	0.479
	0.259	0.285	0.312	0.338	0.365	0.392	0.418	0.445	0.499
0.35	0.340	0.375	0.410	0.445	0.480	0.515	0.550	0.585	0.654
	0.355	0.391	0.427	0.464	0.500	0.537	0.574	0.610	0.683

PINUS RADIATA TARAWERA VOLUME TO 10CM FOR DIAMETER(M) & TOTAL HEIGHT(M)

	HEIGHT										
DIAMETER	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0
0.10	0.054	0.057	0.060	0.063	0.066	0.069	0.072	0.074	0.077	0.080	0.083	0.086
0.11	0.068	0.071	0.075	0.078	0.082	0.085	0.089	0.092	0.096	0.099	0.103	0.106
0.12	0.082	0.087	0.091	0.095	0.099	0.103	0.108	0.112	0.116	0.120	0.124	0.129
0.13	0.098	0.103	0.108	0.113	0.118	0.123	0.128	0.133	0.138	0.143	0.148	0.153
0.14	0.116	0.121	0.127	0.133	0.139	0.144	0.150	0.156	0.161	0.167	0.173	0.179
0.15	0.134	0.141	0.147	0.154	0.161	0.167	0.174	0.180	0.187	0.193	0.200	0.207
0.16	0.154	0.162	0.169	0.177	0.184	0.192	0.199	0.206	0.214	0.221	0.229	0.236
0.17	0.175	0.184	0.192	0.201	0.209	0.218	0.226	0.234	0.243	0.251	0.260	0.268
0.18	0.198	0.207	0.217	0.226	0.236	0.245	0.255	0.264	0.273	0.283	0.292	0.302
0.19	0.222	0.232	0.243	0.253	0.264	0.274	0.285	0.295	0.306	0.316	0.327	0.337
0.20	0.247	0.258	0.270	0.282	0.293	0.305	0.317	0.328	0.340	0.352	0.363	0.375
0.21	0.273	0.286	0.299	0.312	0.324	0.337	0.350	0.363	0.376	0.389	0.402	0.414
0.22	0.301	0.315	0.329	0.343	0.357	0.371	0.385	0.399	0.414	0.428	0.442	0.456
0.23	0.329	0.345	0.360	0.376	0.391	0.407	0.422	0.437	0.453	0.468	0.484	0.499
0.24	0.360	0.376	0.393	0.410	0.427	0.444	0.460	0.477	0.494	0.511	0.528	0.544
0.25	0.391	0.409	0.428	0.446	0.464	0.482	0.500	0.519	0.537	0.555	0.573	0.592
0.26	0.424	0.443	0.463	0.483	0.503	0.522	0.542	0.562	0.582	0.601	0.621	0.641
0.27	0.458	0.479	0.500	0.522	0.543	0.564	0.585	0.607	0.628	0.649	0.670	0.692
0.28	0.493	0.516	0.539	0.562	0.585	0.607	0.630	0.653	0.676	0.699	0.722	0.745
0.29	0.530	0.554	0.579	0.603	0.628	0.652	0.677	0.701	0.726	0.751	0.775	0.800
0.30	0.568	0.594	0.620	0.646	0.673	0.699	0.725	0.751	0.778	0.804	0.830	0.856
0.31	0.607	0.635	0.663	0.691	0.719	0.747	0.775	0.803	0.831	0.859	0.887	0.915
0.32	0.647	0.677	0.707	0.737	0.767	0.797	0.826	0.856	0.886	0.916	0.946	0.976
0.33	0.689	0.721	0.752	0.784	0.816	0.848	0.879	0.911	0.943	0.975	1.007	1.038
0.34	0.732	0.766	0.799	0.833	0.867	0.900	0.934	0.968	1.002	1.035	1.069	1.103
0.35	0.776	0.812	0.848	0.883	0.919	0.955	0.991	1.026	1.062	1.098	1.134	1.169
0.36	0.822	0.860	0.897	0.935	0.973	1.011	1.049	1.086	1.124	1.162	1.200	1.238
0.37	0.869	0.909	0.948	0.988	1.028	1.068	1.108	1.148	1.188	1.228	1.268	1.308
0.38	0.917	0.959	1.001	1.043	1.085	1.127	1.169	1.212	1.254	1.296	1.338	1.380
0.39	0.966	1.011	1.055	1.099	1.144	1.188	1.232	1.277	1.321	1.366	1.410	1.454
0.40	1.017	1.064	1.110	1.157	1.204	1.250	1.297	1.344	1.390	1.437	1.484	1.530
0.41	1.069	1.118	1.167	1.216	1.265	1.314	1.363	1.412	1.461	1.510	1.559	1.608
0.42	1.122	1.174	1.225	1.277	1.328	1.379	1.431	1.482	1.534	1.585	1.637	1.688
0.43	1.177	1.231	1.285	1.339	1.392	1.446	1.500	1.554	1.608	1.662	1.716	1.770
0.44	1.233	1.289	1.345	1.402	1.458	1.515	1.571	1.628	1.684	1.741	1.797	1.854
0.45	1.290	1.349	1.408	1.467	1.526	1.585	1.644	1.703	1.762	1.821	1.880	1.940
0.46	1.348	1.410	1.472	1.533	1.595	1.657	1.718	1.780	1.842	1.904	1.965	2.027
0.47	1.408	1.472	1.537	1.601	1.666	1.730	1.794	1.859	1.923	1.988	2.052	2.117
0.48	1.469	1.536	1.603	1.670	1.738	1.805	1.872	1.939	2.006	2.074	2.141	2.208
0.49	1.531	1.601	1.671	1.741	1.811	1.881	1.951	2.021	2.091	2.161	2.231	2.302
0.50	1.595	1.667	1.740	1.813	1.886	1.959	2.032	2.105	2.178	2.251	2.324	2.397
0.51	1.659	1.735	1.811	1.887	1.963	2.039	2.115	2.191	2.266	2.342	2.418	2.494
0.52	1.725	1.804	1.883	1.962	2.041	2.120	2.199	2.278	2.357	2.435	2.514	2.593
0.53	1.793	1.875	1.957	2.039	2.121	2.203	2.285	2.367	2.448	2.530	2.612	2.694

Table 10.2

0.57	2.075	2.170	2.265	2.360	2.454	2.549	2.644	2.739	2.834
0.58	2.149	2.247	2.345	2.444	2.542	2.640	2.738	2.836	2.934
0.59	2.224	2.326	2.427	2.529	2.630	2.732	2.834	2.935	3.037

CONFIDENCE LIMITS(95%)

0.10	0.046	0.049	0.052	0.055	0.058	0.061	0.064	0.067	0.070
	0.062	0.065	0.067	0.070	0.073	0.076	0.079	0.082	0.085
0.15	0.128	0.134	0.141	0.148	0.154	0.161	0.167	0.174	0.181
	0.141	0.147	0.154	0.160	0.167	0.173	0.180	0.187	0.193
0.20	0.240	0.252	0.264	0.275	0.287	0.298	0.310	0.321	0.333
	0.253	0.265	0.276	0.288	0.300	0.312	0.324	0.335	0.347
0.25	0.383	0.401	0.419	0.437	0.454	0.472	0.490	0.508	0.526
	0.399	0.418	0.436	0.455	0.473	0.492	0.511	0.529	0.548
0.30	0.556	0.581	0.607	0.632	0.658	0.684	0.709	0.735	0.760
	0.579	0.606	0.633	0.660	0.687	0.714	0.741	0.768	0.795
0.35	0.759	0.794	0.828	0.863	0.898	0.933	0.967	1.002	1.037
	0.793	0.830	0.867	0.904	0.940	0.977	1.014	1.050	1.087
0.40	0.993	1.038	1.084	1.129	1.174	1.220	1.265	1.311	1.356
	1.041	1.089	1.137	1.185	1.233	1.281	1.329	1.377	1.425
0.45	1.258	1.316	1.373	1.430	1.488	1.545	1.603	1.660	1.717
	1.321	1.382	1.443	1.503	1.564	1.625	1.686	1.746	1.807
0.50	1.554	1.625	1.696	1.767	1.838	1.909	1.980	2.050	2.121
	1.635	1.710	1.785	1.860	1.935	2.010	2.085	2.160	2.235
0.55	1.882	1.968	2.053	2.139	2.225	2.310	2.396	2.482	2.568
	1.981	2.072	2.163	2.254	2.344	2.435	2.526	2.617	2.707

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CHAPTER 11

DISTRIBUTION OF TREE VOLUME BY WOODAGE

11.1 Prediction of Mean Wood Age

Preceding chapters have outlined the method of estimating individual tree volume; by predicting diameter growth, height growth and from these two, volume. The distribution of this volume by wood-age is calculated in two further steps. First, Mean Wood Age is predicted, then from mean wood age and other tree parameters the distribution of volume by wood age is predicted and applied to the total volume.

Data for the prediction of mean wood age and the distribution of volume by wood age were derived from a sub-set of the volume data. For three of the plots felled to obtain volumes, trees were selected for stem analysis.

The trees were selected at random from amongst the malform-free trees at the rate of three per 4cm dbh (ob) class per plot. In addition a fourth plot, within the experimental stands but not formally part of the experiment was felled in 1980. This plot had been thinned in 1970 to 200 stems/ha and thus provided examples of large fast grown trees. A total of 60 trees were thus sampled, the distribution by plot is shown in Table 11.1.

The field procedure after felling was to trim off the branches to provide access to the trunk then to measure the height. Next the height of every whorl (strictly-branch pseudo-cluster) was measured and marked on the tree. A thin disc was cut from the butt and retained for measurement. Radiata pine is usually a multi-nodal tree forming more than one node each year. However, by carefully sawing through the trunk and counting

Table 11.1. Trees Sampled by Stem Analysis

Planting espacement	Age at felling	Number
2.1m	14 yrs.	16
2.7m	14 yrs.	16
1.8m	15 yrs.	17
2.1m thinned	17 yrs.	11
		60

tree rings the whorls where the terminal shoot had formed a winter resting bud were identified. Such whorls have one less annual ring above the whorl than below it. This indicates the point at which annual height growth has paused over winter and the height of the whorl at this point indicates the height of the tree at the appropriate age (see Figure 4.1).

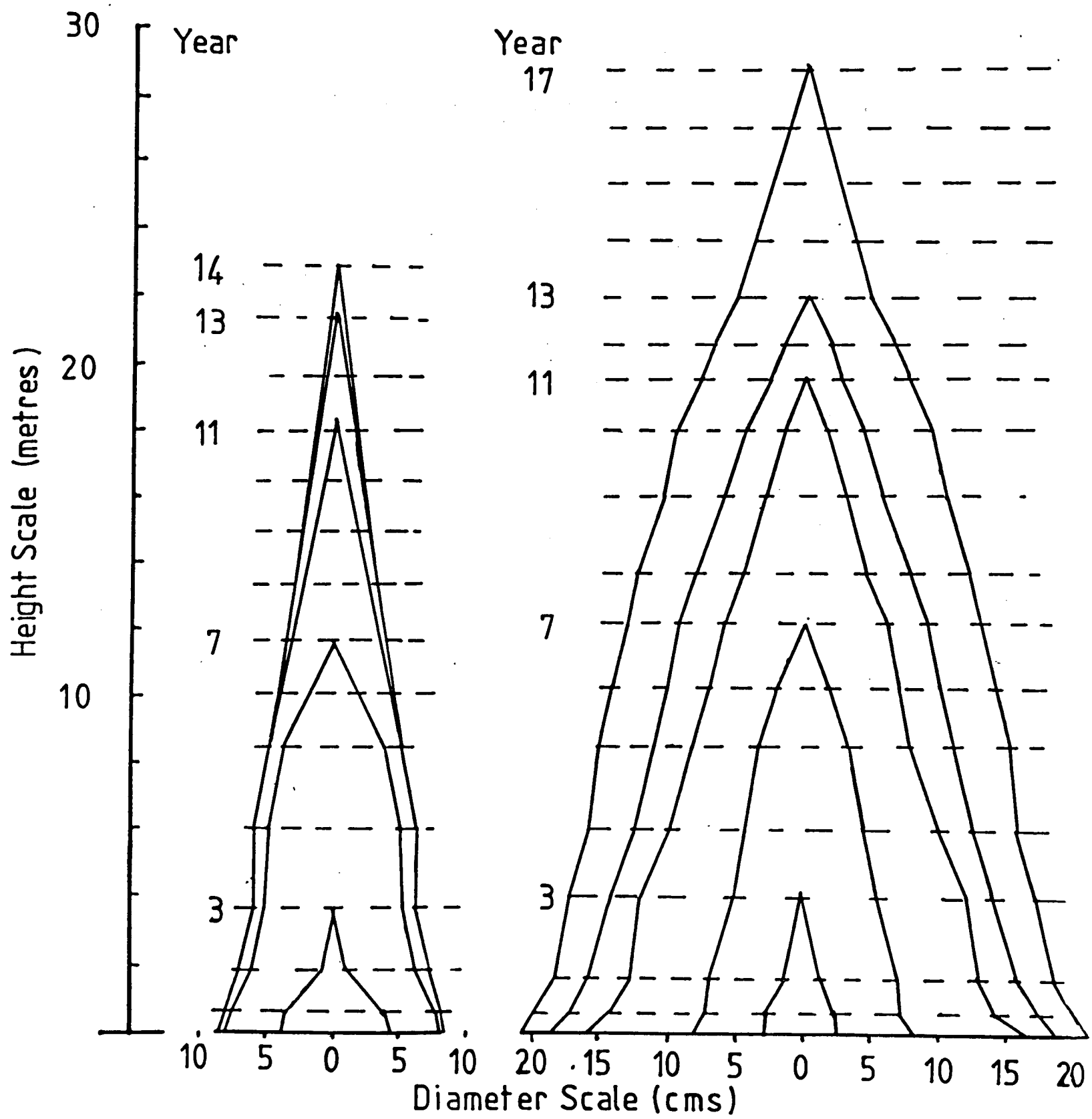
Immediately above each such whorl, a disc was cut from the trunk for measurement. The disc was taken from above the whorl because it is impossible to measure ring widths at the exact point where height growth finishes for the year since this is also where the branches originate from the pith. Subsequent growth by the branches distorts the ring pattern and results in nodal swelling. By taking the disc from above the whorl, just above the nodal swelling, volume may be underestimated. This would apply to all ages, however, and the data obtained by this method were only used to calculate the proportion of volume by wood age; tree volume itself being obtained by the method given earlier. Discs were removed up to a diameter of 10cm inside bark.

When all the discs for a tree were obtained, the ring widths were measured. Two 'diameters' were drawn at right angles to each other across the disc. If the disc was not round, these lines went through the pith to form the major and minor axes of an elipse. The distance from the

centre of the pith to each ring (outer edge of the late-wood band) was measured along the four radii. the four values thus obtained were meaned to calculate volume. By means of a computer program (given as Appendix 5), the volume of wood for each wood age was calculated and a weighted average mean wood age computed. Since stem analysis is a method for examining past growth, the calculations could be repeated as if each tree had been felled one year earlier. That is the outer sheath, representing one year's physical growth but containing wood of all ages from 0.5 to the age of the tree, could in effect be stripped off and a new set of volumes computed. This process of calculation was performed for each tree for the age of felling back to six years. The formula used for calculating sectional volume was Smalians, except for wood age 0.5 which always has an upper diameter of 0 and for which the formula for the volume of a cone was used.

The range of mean wood age (MWA) values varied in the sample obtained here from 3.6 years for a slow growing tree felled at age 14 to 7.8 years for a fast grown tree felled at age 17. The reason for such a range can be understood by comparing the two scale drawings in Figure 11.1. For many suppressed trees growth at breast height is almost non-existent most growth effort going into increasing height and upper diameter. This diversion of diminished growth potential into regions that are essential to maintain competitive status is undoubtedly a response to the intense pressure for light faced by all sub-dominant or suppressed trees. The result is, however, that only young wood is produced by such trees. In extreme cases MWA decreases with increasing age because no mature wood is produced. In the case of fast growing trees the converse is true. Dominant trees tend to increase in diameter throughout the length of stem producing young wood in the upper crown and more mature wood at

Figure 11.1 Scale Drawings of Trees of Highest and Lowest M.W.A.



Regime :- unthinned thinned at 7years

the base of the trunk. Because MWA is a weighted average of all the wood produced by a tree (to a 10cm top limit) and because a fast growing tree produces young wood as well as mature wood, the numerical value changes slowly with increasing proportion of mature wood. This detracts for its use alone as an index of wood quality.

Of the 60 trees subject to stem analyais, 50 were used to derive the MWA model; the other ten being used as validation data. The validation data set was subjectively chosen, two from each plot selected close to the highest or lowest value of MWA for the plot; plus two more from the 15 year old plot selected from the middle of the range.

Before the model could be developed, however, a model for bark thickness was needed. This was necessary because all measurements of diameter obtained by stem analysis are inside bark whereas estimates of tree diameter are outside bark. Data for a bark model were constructed from 72 measurements of diameter and bark thickness. These were: all 12 trees from the 17 year old plot plus the first 20 trees in each of the other three plots. The NONLIN package was used but although a non-linear relationship had the highest coefficient of determination, this was only minutely greater than the value for the linear form and this simpler form was adopted. The bark model is

$$2BT = (DBH \times 0.1288902) - 0.006196855$$

$r^2 = 0.777$

where 2BT = twice bark thickness, and

DBH = diameter at breast height, inside bark.

The MWA model was based on multiple linear regression analysis and was developed using the program CGMP. There were 470 sets of data.

The equation is

Variable	Coefficient	T-value
Intercept	-17.3816	-4.25
Taper	0.0734	4.90
Height	-0.8909	-10.15
DBH (ob)	47.9958	7.83
Age x taper	-0.006376	-7.73
Age x height	0.05523	8.82
Age x DBH	-2.4126	-6.10
Ln age	3.5031	7.20
Ln taper	3.0892	2.73

r^2 = 0.858

F ratio 309.95

Where taper is height (m) divided by diameter (m).

From the plot of residuals it was observed that 93% of predicted values lie between +0.85 and -0.51 of the actual value.

11.2 Validation of MWA Model

The validation data comprised 119 observations of MWA from ten trees. When actual and predicted values were compared the smallest difference was -0.014 and the greatest +1.077. The range in actual values compared was 3.189 to 7.532. Results for all 119 comparisons were:

Average Actual Value	4.630
Average Predicted Value	4.605
Mean Squared Residual	0.16731

The model seems free from overall bias and the average error is acceptable.

11.3 Prediction of Mean Wood Age Distribution

It was decided to use the Weibull probability density function to predict the percentage distribution of volume by wood age. This function and its use for quantifying diameter distributions is described by Bailey and Dell (1973). They trace the origin of the method to two groups of authors, Fisher and Tippett (1928) and Weibull (1939) who derived the function independently of each other. The function is

$$f(x) = (c/b)\ (x/b)^{c-1}\ \exp\left[\ -(x/b)^{c}\ \right]$$

where b is a scale parameter and c is a shape parameter. A three parameter model can be derived by substituting

$$x = y-a$$

and in this case a is the location parameter. The advantage of this model is that by changing the value of parameters b and c the model will describe all distribution curves from reverse J to positively or negatively skewed unimodal distributions. the form of equation used here was the cumulative distribution function, derived by integrating the general function and simplifying. It is of the form $F(x) = 1 - \exp\left[\ -(x/b)^{c}\ \right]$

The probability of values occupying any one class in a frequency distribution can be found by predicting the accumulative probability to the end and beginning of the class and subtracting the two values.

To define the shape of a given distribution it is first necessary to estimate the values of the b and c parameters. To do this the method of D'Agostino (1971) was used. This is described as a linear method of estimating the parameters when a sample of the frequency observations is known and 'the proportion of observations from the sample available

for the estimates (is known)'. This method is said to be optimal for large samples and in this case all frequencies were known, and the sum of known probabilities equalled one. For wood age distribution the lowest age is zero and this is therefore the value of the a parameter. To predict b and c for a given distribution a sample of distributions was selected, the Weibull parameters b and c estimated and these values modelled by correlating with already defined variables such as MWA.

The range in value of MWA represented in the data set was:

	Minimum	Maximum
at 6 yrs.	3.14 yrs	4.366 yrs
at clearfelling	3.64 yrs	7.838 yrs

each value being represented by only one tree.

To obtain the sample distributions all the four trees with extreme values were included. The range between minimum and maximum values at clearfelling was divided into ten intervals and trees subjectively chosen close to the value of the intervals, from all four plots. The range between minimum and maximum values at six years was fairly well covered by the trees chosen in this way, but an additional two trees were selected to fill a gap in the data close to the minimum value. This gave a sample of 12 trees with values of MWA evenly distributed along the range from minimum to maximum values both at clearfelling and at age six years.

In total, the 12 trees contributed 120 distributions when all ages were included. The b and c parameters for the Weibull function were calculated for all 120 distributions. Values of b were regressed with MWA separately by age using NONLIN. In each case the linear model resulted

in a very high explanation of variation (r^2 from .982 to 0.997) and there was little variation in either slope or intercept. All values were then pooled and the linear relationship between MWA and b recalculated; r^2 equalled 0.984. This indicates a good explanation so the linear model was adopted.

The Weibull parameter c, which influences the shape of the distribution was less easily predicted. When regressed against MWA for each age the quadratic model gave a good explanation (r^2 = .798 to .983) but the coefficients of the model did not form a coherent pattern with time. Using the program CGMP, multiple linear regressions with high explanation were developed for y = c and y = $Log_e C$. The log transformation of c was preferred however because with this model the residuals (Actual value of c - Predicted value) were distributed with less bias than for the regression with untransformed values of c.

The two models to calculate b and c are:

$$b = 1.224112\ MWA - 0.2910628$$

$$r^2 = 0.984$$

$Log_e C$ =

Variable	Coefficient	T-value
Intercept	4.363046	21.98
Age	0.3416393	10.87
MWA	1.065322	9.36
Age x MWA	-0.03633757	-10.22
Log_e age	-2.870408	-15.43
Log_e MWA	-2.314679	-6.00

r^2 = 0.96441 F. ratio 474.28

11.4 Validation of Distribution Model

A computer program in FORTRAN was written incorporating these equations to estimate values for b and c and to compare actual and predicted distributions for a validation data-set.

The validation sample comprised three trees subjectively chosen from each of the four plots. Two ages were chosen for each tree giving a total of 24 distributions for comparison. Both the trees and ages were chosen to reflect the whole range of growth rates and MWA values. The text of the test program is given below as well as the results of the comparison. In most cases actual and predicted distributions agreed closely, however, slow growing trees with MWA close to four have a greater volume in wood-age close to the mean than is predicted. In the worst case found, trees with 25% of their volume in the 3.5 and 4.5 wood age classes were predicted to have only 18% in those classes. Such trees would be amongst the smallest in the stand and errors amongst trees of these sizes would have the least effect on a stand basis. In view of the close agreement between actual and predicted for average to fast growing trees, the model is regarded as satisfactory.

```
      PROGRAM WEISOLVE
      INTEGER AGE
      REAL MWA
C SOLVES FOR % DISTRIBUTION USING WEIBULL FUNCTION
      DIMENSION DIS(20),PF(20),XX(20),DIF(20)
      WRITE(2,40)
   40 FORMAT(1H1,//,15X,'COMPARISON OF DISTRIBUTIONS OF WOOD AGE')
      WRITE(2,120)
  120 FORMAT(1H ,30X,'(PERCENT)',//)
      WRITE(2,60)
   60 FORMAT(7X,'WOOD-AGE',3X,'ACTUAL FREQUENCY',2X,'PREDIC FREQUENCY',
     61X,'DIFFERENCE')
      WRITE(2,130)
  130 FORMAT(1H ,5X,'----------------------------------------',
     7'----------',//)
      TREE=0.5
      DO 10 I=1,24
      CI=1.0
      READ(1,*)AGE,MWA
      DO 20 J=1,AGE
      READ(1,*)DIS(J)
   20 CONTINUE
      DO 30 L=2,AGE
      XX(L)=XX(L-1)+CI
   30 CONTINUE
      CI=CI*0.5
      A=0.0
      B=(1.224112*MWA)-0.2910628
      C=4.363046+(AGE*0.3416393)+(MWA*1.065332)-(AGE*MWA*0.03633757)
     1-((ALOG(AGE*1.0))*2.870408)-((ALOG(MWA))*2.314679)
      C=EXP(C)
      TOT=100
      DO 100 K=1,AGE
      PF(K)=TOT*(EXP(-((XX(K)-A-CI)/B)**C)
     2-EXP(-((XX(K)-A+CI)/B)**C))
  100 CONTINUE
      DO 50 L=1,AGE
      DIF(L)=DIS(L)-PF(L)
   50 CONTINUE
      TREE=TREE+0.5
      NO=INT(TREE)
      WRITE(2,110)NO,AGE,MWA
  110 FORMAT(17X,'TREE NO ',I3,'   AGE= ',I3,'  MWA= ',F5.3,/)
      DO 70 M=1,AGE
      WRITE(2,80)XX(M),DIS(M),PF(M),DIF(M)
   80 FORMAT(10X,F4.1,10X,F5.2,10X,F5.2,10X,F6.2)
   70 CONTINUE
      WRITE(2,90)
   90 FORMAT(//)
   10 CONTINUE
      STOP
      END
```

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Table 11.2

COMPARISON OF DISTRIBUTIONS OF WOOD AGE
(PERCENT)

WOOD-AGE	ACTUAL FREQUENCY	PREDIC FREQUENCY	DIFFERENCE
TREE NO 1 AGE= 6 MWA= 3.431			
0.5	0.49	0.60	-0.11
1.5	8.35	7.16	1.19
2.5	26.79	23.18	3.61
3.5	35.50	35.46	0.04
4.5	19.72	25.57	-5.85
5.5	9.20	7.36	1.84
TREE NO 1 AGE= 14 MWA= 5.662			
0.5	1.49	2.11	-0.62
1.5	7.91	6.25	1.66
2.5	11.41	9.68	1.73
3.5	13.36	11.98	1.38
4.5	12.35	12.96	-0.61
5.5	11.44	12.70	-1.26
6.5	10.20	11.47	-1.27
7.5	9.00	9.63	-0.63
8.5	7.62	7.57	0.05
9.5	6.14	5.60	0.54
10.5	4.22	3.90	0.32
11.5	2.74	2.56	0.18
12.5	1.55	1.59	-0.04
13.5	0.57	0.94	-0.37
TREE NO 2 AGE= 8 MWA= 3.776			
0.5	1.24	2.02	-0.78
1.5	10.42	10.04	0.38
2.5	24.23	19.36	4.87
3.5	21.11	24.08	-2.97
4.5	19.25	21.38	-2.13
5.5	16.50	13.84	2.66
6.5	4.93	6.50	-1.57
7.5	2.34	2.18	0.16
TREE NO 2 AGE= 12 MWA= 3.972			
0.5	3.52	5.49	-1.97
1.5	17.76	13.41	4.35
2.5	19.33	17.40	1.93
3.5	16.42	17.72	-1.30
4.5	12.99	15.40	-2.41
5.5	10.99	11.80	-0.81
6.5	7.74	8.12	-0.38
7.5	5.35	5.06	0.29
8.5	3.42	2.87	0.55
9.5	1.70	1.50	0.20
10.5	0.50	0.72	-0.22
11.5	0.28	0.32	-0.04

TREE NO 3 AGE= 9 MWA= 4.207

0.5	1.17	1.94	-0.77
1.5	9.76	8.47	1.29
2.5	17.92	15.61	2.31
3.5	19.94	19.99	-0.05
4.5	17.98	19.82	-1.84
5.5	16.46	15.72	0.74
6.5	9.58	10.08	-0.50
7.5	3.91	5.22	-1.31
8.5	3.27	2.18	1.09

TREE NO 3 AGE= 12 MWA= 4.363

0.5	2.77	4.19	-1.42
1.5	14.58	11.01	3.57
2.5	16.72	15.24	1.48
3.5	15.30	16.58	-1.28
4.5	14.24	15.47	-1.23
5.5	12.39	12.80	-0.41
6.5	9.38	9.55	-0.17
7.5	6.55	6.49	0.06
8.5	3.91	4.04	-0.13
9.5	2.37	2.32	0.05
10.5	1.08	1.23	-0.15
11.5	0.73	0.60	0.13

TREE NO 4 AGE= 6 MWA= 3.524

0.5	1.23	0.49	0.74
1.5	8.64	6.21	2.43
2.5	21.69	21.13	0.56
3.5	32.05	34.59	-2.54
4.5	27.71	27.51	0.20
5.5	8.68	9.08	-0.40

TREE NO 4 AGE= 11 MWA= 5.513

0.5	0.87	0.77	0.10
1.5	4.66	3.83	0.83
2.5	8.37	8.06	0.31
3.5	11.55	12.25	-0.70
4.5	15.18	15.18	-0.00
5.5	17.60	16.03	1.57
6.5	15.73	14.67	1.06
7.5	11.96	11.70	0.26
8.5	9.00	8.14	0.86
9.5	3.91	4.93	-1.02
10.5	1.86	2.59	-0.73

TREE NO 5 AGE= 13 MWA= 6.094

0.5	0.89	0.90	-0.01
1.5	4.84	3.72	1.12
2.5	7.58	7.10	0.48
3.5	10.71	10.24	0.47
4.5	12.15	12.51	-0.36
5.5	13.49	13.51	-0.02
6.5	13.60	13.15	0.45
7.5	11.92	11.63	0.29
8.5	9.67	9.40	0.27
9.5	7.37	6.96	0.41
10.5	4.39	4.72	-0.33
11.5	2.03	2.93	-0.90
12.5	1.37	1.67	-0.30

TREE NO 5 AGE= 17 MWA= 7.528

0.5	0.75	1.03	-0.28
1.5	3.76	3.28	0.48
2.5	5.46	5.46	0.00
3.5	7.57	7.32	0.25
4.5	9.05	8.72	0.33
5.5	9.70	9.58	0.12
6.5	9.98	9.87	0.11
7.5	10.06	9.63	0.43
8.5	9.47	8.97	0.50
9.5	8.87	8.00	0.87
10.5	7.69	6.85	0.84
11.5	6.16	5.64	0.52
12.5	4.68	4.48	0.20
13.5	3.28	3.43	-0.15
14.5	2.08	2.53	-0.45
15.5	0.86	1.81	-0.95
16.5	0.60	1.25	-0.65

TREE NO 6 AGE= 9 MWA= 4.391

0.5	0.71	1.49	-0.78
1.5	5.98	7.12	-1.14
2.5	11.44	14.00	-2.56
3.5	17.39	19.03	-1.64
4.5	19.11	19.99	-0.88
5.5	15.34	16.79	-0.95
6.5	13.25	11.38	1.87
7.5	11.48	6.21	5.27
8.5	4.90	2.72	2.08

TREE NO 6 AGE= 13 MWA= 6.141

0.5	0.68	0.84	-0.16
1.5	4.09	3.55	0.54
2.5	7.30	6.88	0.42
3.5	10.07	10.04	0.03
4.5	13.24	12.38	0.86
5.5	13.79	13.48	0.31
6.5	13.63	13.22	0.41
7.5	11.00	11.77	-0.77
8.5	9.64	9.56	0.08
9.5	6.89	7.11	-0.22
10.5	4.46	4.84	-0.38
11.5	3.07	3.01	0.04
12.5	1.19	1.71	-0.52

TREE NO 7 AGE= 10 MWA= 4.422

0.5	0.21	2.31	-2.10
1.5	5.06	8.55	-3.49
2.5	14.07	14.47	-0.40
3.5	25.45	17.90	7.55
4.5	25.19	17.94	7.25
5.5	15.41	15.11	0.30
6.5	5.87	10.86	-4.99
7.5	2.98	6.71	-3.73
8.5	3.03	3.57	-0.54
9.5	2.72	1.63	1.09

TREE NO 7 AGE= 15 MWA= 3.731

0.5	2.12	6.70	-4.58
1.5	13.61	15.24	-1.63
2.5	22.70	18.70	4.00
3.5	24.59	18.07	6.52
4.5	18.66	14.91	3.75
5.5	7.32	10.85	-3.53
6.5	3.68	7.09	-3.41
7.5	3.41	4.19	-0.78
8.5	2.32	2.27	0.05
9.5	1.24	1.12	0.12
10.5	0.28	0.51	-0.23
11.5	0.05	0.22	-0.17
12.5	0.00	0.08	-0.08
13.5	0.00	0.03	-0.03
14.5	0.00	0.01	-0.01

TREE NO 8 AGE= 10 MWA= 4.293

0.5	1.34	2.68	-1.34
1.5	9.65	9.45	0.20
2.5	16.90	15.40	1.50
3.5	19.25	18.42	0.83
4.5	19.38	17.87	1.51
5.5	13.75	14.58	-0.83
6.5	10.27	10.16	0.11
7.5	5.94	6.09	-0.15
8.5	2.94	3.15	-0.21
9.5	0.56	1.41	-0.85

TREE NO 8 AGE= 15 MWA= 5.980

0.5	1.07	2.06	-0.99
1.5	6.50	5.85	0.65
2.5	10.59	8.93	1.66
3.5	12.92	11.01	1.91
4.5	13.02	12.01	1.01
5.5	11.52	11.96	-0.44
6.5	9.99	11.09	-1.10
7.5	8.26	9.65	-1.39
8.5	7.12	7.92	-0.80
9.5	5.95	6.17	-0.22
10.5	5.01	4.57	0.44
11.5	4.17	3.23	0.94
12.5	2.61	2.18	0.43
13.5	1.02	1.40	-0.38
14.5	0.20	0.86	-0.66

TREE NO 9 AGE= 12 MWA= 4.668

0.5	0.28	3.25	-2.97
1.5	4.82	9.27	-4.45
2.5	14.24	13.62	0.62
3.5	22.96	15.66	7.30
4.5	23.97	15.41	8.56
5.5	14.00	13.44	0.56
6.5	7.71	10.58	-2.87
7.5	3.49	7.58	-4.09
8.5	2.76	4.97	-2.21
9.5	2.80	3.00	-0.20
10.5	1.90	1.67	0.23
11.5	1.07	0.86	0.21

TREE NO 9 AGE= 13 MWA= 4.302

0.5	0.83	5.01	-4.18
1.5	8.36	11.90	-3.54
2.5	19.89	15.54	4.35
3.5	23.49	16.28	7.21
4.5	19.90	14.83	5.07
5.5	20.37	12.14	8.23
6.5	6.01	9.07	-3.06
7.5	3.33	6.25	-2.92
8.5	2.90	3.99	-1.09
9.5	2.62	2.38	0.24
10.5	1.46	1.32	0.14
11.5	0.70	0.69	0.01
12.5	0.15	0.34	-0.19

TREE NO 10 AGE= 7 MWA= 4.175

0.5	0.28	0.42	-0.14
1.5	5.71	4.16	1.55
2.5	14.16	12.90	1.26
3.5	21.95	23.23	-1.28
4.5	27.08	27.19	-0.11
5.5	25.67	20.37	5.30
6.5	5.16	9.17	-4.01

TREE NO 10 AGE= 12 MWA= 4.708

0.5	1.45	3.14	-1.69
1.5	9.74	9.05	0.69
2.5	14.30	13.41	0.89
3.5	16.40	15.53	0.87
4.5	16.26	15.39	0.87
5.5	14.71	13.52	1.19
6.5	10.67	10.71	-0.04
7.5	7.31	7.72	-0.41
8.5	4.89	5.09	-0.20
9.5	2.61	3.09	-0.48
10.5	1.37	1.73	-0.36
11.5	0.29	0.89	-0.60

TREE NO 11 AGE= 8 MWA= 3.606

0.5	1.70	2.52	-0.82
1.5	13.00	11.71	1.29
2.5	21.48	21.29	0.19
3.5	23.91	24.81	-0.90
4.5	22.24	20.43	1.81
5.5	12.73	12.13	0.60
6.5	3.99	5.17	-1.18
7.5	0.90	1.56	-0.66

TREE NO 11 AGE= 12 MWA= 4.345

0.5	2.54	4.25	-1.71
1.5	12.81	11.12	1.69
2.5	16.70	15.34	1.36
3.5	17.28	16.64	0.64
4.5	16.49	15.47	1.02
5.5	11.69	12.76	-1.07
6.5	8.31	9.49	-1.18
7.5	6.38	6.43	-0.05
8.5	3.99	3.99	0.00
9.5	2.68	2.28	0.40
10.5	0.91	1.20	-0.29
11.5	0.22	0.59	-0.37

TREE NO 12 AGE= 9 MWA= 3.744

0.5	2.92	3.37	-0.45
1.5	14.72	12.32	2.40
2.5	19.77	19.67	0.10
3.5	22.30	21.87	0.43
4.5	16.74	18.69	-1.95
5.5	11.22	12.68	-1.46
6.5	7.49	6.91	0.58
7.5	3.52	3.03	0.49
8.5	1.32	1.07	0.25

TREE NO 12 AGE= 14 MWA= 5.290

0.5	2.05	2.91	-0.86
1.5	9.52	7.75	1.77
2.5	12.29	11.22	1.07
3.5	14.03	13.11	0.92
4.5	13.22	13.48	-0.26
5.5	12.00	12.59	-0.59
6.5	10.16	10.88	-0.72
7.5	8.58	8.76	-0.18
8.5	6.75	6.63	0.12
9.5	4.60	4.73	-0.13
10.5	3.03	3.19	-0.16
11.5	2.35	2.04	0.31
12.5	1.02	1.23	-0.21
13.5	0.40	0.71	-0.31

CHAPTER 12

PREDICTION OF STAND VOLUME BY WOOD-AGE

12.1 Results using TOTALMOD

Previous chapters have listed the development of models to predict: diameter growth, height, volume, mean wood-age and distribution of volume by wood-age. These were linked in a computer program called TOTALMOD (written in FORTRAN) so that from an initial set of diameter measurements at a known age and a stand map, the distribution of stand volume by wood-age is finally predicted. The computer program is given as Appendix 3.

12.2 A Comparison Using Actual Diameter Values

The results of the full model using the validation data-set are given in Table 12.1. Validating the total model is difficult as no data are available where the growth, spatial arrangement and volume distribution are known for the same stand. For the five main models now linked in the program TOTALMOD all but the model of diameter growth were shown to closely predict actual values when tested. Because the data for tree diameters are known up to 17 years of age, it is possible to substitute actual diameter distribution for predicted diameter distribution; and by using the same models for subsequent estimates provide a basis of comparison which will highlight the efficacy of the diameter model. Results using actual diameters are also given in Table 12.1 under the heading 'Comparison'.

It can be seen that in most cases volume per plot based on predicted diameters is predicted well when compared with volume based on actual diameters. Usually the difference is less than $\pm 10\%$. There are some important exceptions; unthinned plots and plots thinned conservatively

Table 12.1. Results of Full Model at age 17 years

Regime*	Plot*	Volume per plot (m^3)			Mean Wood Age (years)		
		Model	Comparison	Difference (%)	Model	Comparison	Difference
T380E	9x1	38.2	34.8	+9.8	7.920	7.842	.078
	7x15	32.4	32.5	o	7.721	7.770	-.049
	6x15	33.0	31.7	+4.1	7.727	7.752	-.025
mean		34.5	33.0	+4.5			
T380L	7x14	29.0	30.2	-4.0	7.571	7.621	-.05
	6x10	29.4	29.3	+0.3	7.577	7.609	-.032
mean		29.2	29.8	-1.8			
T380LR	9x3	27.5	26.7	+3.0	7.536	7.495	.041
	7x11	23.7	27.2	-12.9	7.431	7.565	-.134
	6x6	29.7	26.3	+12.9	7.617	7.650	-.033
mean		27.0	26.7	+1.1			
T380-2	7x4	28.8	30.1	-4.3	7.562	7.630	-.068
	6x4	30.3	31.5	-3.8	7.613	7.722	-.109
	4x14	27.3	27.2	+0.4	7.493	7.564	-.071
	4x19	22.1	24.9	-11.2	7.274	7.405	-.131
T500	7x10	33.3	34.9	-4.6	7.493	7.533	-.04
T750	9x9	39.1	37.7	+3.7	7.235	7.183	.052
	7x29	31.3	33.4	-6.3	7.005	7.032	-.027
	6x13	38.3	34.6	+10.7	7.188	7.062	.126
	4x12	32.0	39.0	-17.9	7.048	7.215	-.167
mean		35.2	36.2	-2.8			
T1000	7x19	36.6	36.6	o	7.099	6.958	.141
T1350	4x16	24.5	33.1	-26.0	6.331	6.457	-.126
T500C	7x3	29.6	32.6	-9.2	7.305	7.383	-.078
unthinned	7x18	43.8	37.0	+18.4	6.756	6.656	.1
	6x9	50.1	38.2	+31.2	6.475	6.312	.163
	4x5	27.5	30.6	-10.1	5.890	6.176	-.286

* symbols have the same meaning as in Table 8.10.

(to a high residual stocking) or subject to 'crown' thinning are predicted badly. The volume of one of the unthinned plots was over-estimated by 31%. In these cases the bias already noted in the prediction of diameter is accentuated when the results are expressed as volume.

Where a number of plots have received the same or almost the same thinning treatments they have been aggregated and the mean result given. In all four cases where this has been done, the mean result from the total model agrees closely with the mean result of the comparison based on the actual diameter distribution. This is despite the widely differing estimates obtained in some cases when only one matched pair of plots is considered.

These results and the comparison between predicted volumes derived from the two sources of values for diameter provide a useful test of the diameter model as a tool for volume prediction. In turn, this serves to emphasise the usefulness of evaluating a general purpose model, such as the diameter growth model, as a tool for a specific purpose. Although a comparison with results of diameter prediction (given in Table 8.1) show that plots where diameter was predicted well usually have good volume predictions, the reverse can be true. For example, for the last example (plot 4x5) in Table 8.1, there was only a 1% difference between actual and predicted mean diameter - there was 10% difference between the two sources of volume prediction.

12.3 A Silvicultural Parameter which Indicates Wood Quality

Table 12.1 also gives comparative results of mean wood age predictions There is close agreement between the two sources of MWA. However, the range in values of stand MWA is small - largest is 7.8, smallest 6.2 so that only small deviation between actual and predicted values can be tolerated.

Even the range of MWA for individual trees is not large, at 17 years of age it ranged from 8.2 to 3.2 in this investigation. This casts doubt on the parameter MWA as a useful indicator of stand wood properties. The pattern of changing wood properties with wood age has already been discussed. C own (1980) states that 'although the changes are gradual across the growth zones, the pattern lends itself to the concept of a central low density core, followed by a transition to high density outerwood'. This is a useful concept because although corewood is used in the manufacture of all wood products, it is the outerwood that contributes the more valuable properties to the products. Kibblewhite (1980), suggested that the core should include wood up to 15 years in age, but Crown and Kibblewhite (1980) define corewood as 'rings 1 to 10'. The oldest data available from the field trial reported here is 17 years so for the purposes of evaluating these data, corewood was defined as wood younger than 10 years in wood-age.

The more important component then becomes wood of wood-age greater than 10 years and Table 12.2 shows the volume and proportion of volume available from each plot of wood in this category. By concentrating on a smaller component of total volume, percentage differences between estimates from the total model and the comparison are slightly increased. However, there is close agreement when regime means are compared and the proportion of mature wood is very closely predicted.

The index of comparison introduced here appears to be suitable for comparisons of wood quality. By measuring the quantity of mature wood produced the index measures a parameter that can be directly related to quality and ultimately to value. The earlier index suggested by Grant (1978), i.e. Mean Wood-age, has the problem associated with any index based on a mean value; without information on distribution it is difficult to

Table 12.2. Volume Mature Wood (>-10 years) At Age 17 years

Regime*	Plot*	Volume per plot (m^3)			Proportion of Total (%)	
		Total Model	Comparison	Difference (%)	Total Model	Comparison
T380E	9x1	11.0	9.9	+11.1	28.9	28.3
	7x15	8.8	9.0	-2.2	27.2	27.6
	6x15	9.0	8.7	+3.4	27.2	27.3
mean		9.6	9.2	+4.3	27.8	27.7
T380L	7x14	7.5	7.9	-5.1	25.8	26.3
	6x10	7.6	7.7	-1.3	25.9	26.1
mean		7.6	7.8	-2.6	25.9	26.2
T380LR	9x3	7.1	6.7	+6.0	25.7	25.1
	7x11	5.9	7.0	-15.7	24.7	25.7
	6x6	7.8	7.0	+11.4	26.3	26.7
mean		6.9	6.9	0	25.6	25.8
T380-2	7x4	7.4	7.9	-6.3	25.7	26.4
	6x4	7.9	8.6	-8.1	26.0	27.2
	4x14	6.9	7.0	-1.4	25.1	25.7
	4x19	5.2	6.1	-14.8	23.4	24.5
T500	7x10	8.4	9.0	-6.7	25.1	25.7
T750	9x9	9.1	8.5	+7.1	23.2	22.6
	7x29	6.6	7.2	-8.3	21.2	21.6
	6x13	8.7	7.5	+16.0	22.6	21.7
	4x12	7.0	9.0	-22.2	21.7	23.0
mean		7.9	8.1	-2.5	22.2	22.2
T1000	7x19	8.1	7.7	+5.2	22.2	21.0
T1350	4x16	3.9	5.7	-31.6	16.1	17.7
T500C	7x3	7.0	7.9	-11.4	23.7	24.2
UT2100	7x18	8.4	6.9	+21.7	19.2	18.7
2500	6x9	8.6	6.1	+41.0	17.2	15.9
5000	4x5	3.5	4.6	-23.9	12.9	15.0

* Symbols as for table 8.10.

relate directly to quantity or value. Because MWA is a weighted average of wood of all wood ages, quite drastic differences in silviculture produce only small apparent changes in MWA. This can be seen from Grant (1978) and from Table 12.1. Volume of mature wood however varies quite drastically between regimes. In Table 12.3 volumes of mature wood are expressed in cubic metres per hectare - derived from the actual diameter distributions. The volume available from the highest producing regime (an early thinning to 380s/ha) is about twice that from the lowest producing regime (plant at 1.3m, no thinning). In the table, plots are arranged in order by regime, from lowest stocking level/earliest thinning to highest stocking level/ latest or no thinning.

The results show that by age 17 years the regime where stocking was reduced to 380 stems/hectare at age six has produced the greatest volume of mature wood. This is despite the fact that stands at a higher stocking level contain more wood of all ages (see Table 12.1). The next highest production of mature wood is from a regime where twice the stocking level was retained. In this case, high volume (due to the high stocking) has resulted in a higher production of mature wood despite a low proportion of the total volume that is of wood older than 10 years.

Table 12.3. Volume of Mature Wood per Hectare (≥-10 years) at 17 years (m^3/ha)

Regime	Plot*	Volume (based on actual diameter)
Thinned to 380/ha	9x1	163
	7x15	148
	6x15	143
		151
Thinned to 380/ha late	7x14	130
	6x10	126
		128
Thinned to 380/ha late by rows	9x3	110
	7x11	115
	6x6	115
		113
Thinned to 380/ha 2 stages	7x4	130
	6x4	141
	4x14	115
	4x19	100
Thinned to 500/ha	7x10	148
Thinned to 750/ha	9x9	140
	7x29	119
	6x13	124
	4x12	148
		133
Thinned to 1000/ha	7x19	127
Thinned to 1350/ha	4x16	94
Thinned to 500/ha crown	7x3	130
Unthinned 2250/ha	7x18	114
3000/ha	6x9	100
5000/ha	4x5	76

* symbols as defined for Table 8.10.

CHAPTER 13

CONCLUSIONS

A method of linking thinning treatment to the value of a silvicultural parameter which is also related to intrinsic wood properties has been developed. This means that for plantation radiata pine grown in one location in New Zealand, wood quality can be predicted if stand data and silviculture are known.

The stand parameter which seems to best indicate wood quality and which is also sensitive to changes in silviculture is 'volume of mature wood'. For this work mature wood is defined as wood of wood age greater than 10 years. For regimes involving thinning from below the value of this parameter can be satisfactorily predicted by a system of models which estimate, in turn: diameter, height, volume, mean-wood-age and distribution of volume by wood-age. Bias in the diameter model means that the total model system is unsuitable as a predictive tool for unthinned stands. However, if the actual diameter distribution is known for unthinned stands of a given age, then the volume of mature wood can then be estimated.

If it is accepted that the parameter introduced here - volume of mature wood - indicates wood properties, then the results of the model system for a plot series covering a wide range of silvicultural regimes indicates that the timing and severity of thinning strongly influences the properties of the wood yield. This influence is in addition to the widely accepted influence of rotation age.

CHAPTER 14

DISCUSSION OF RESULTS AND CONCLUSIONS

The importance of producing wood of high quality for its intended end use has long been recognised in New Zealand. In 1980 a special Task Force was set up to investigate the links between silviculture and wood properties. This group of investigators concentrated mainly on external properties such as timber strength and amount of 'clear' timber although the relationships between intrinsic properties such as density and strength were also determined. There has been concern too that the forest plantation resource has changed in character and that some deterioration in intrinsic properties may have occurred. This is discussed in detail by Bunn (1981) but his concern and that of Harris and others (1976) earlier was mainly with a reduction in rotation age. Cown (1974) was more specific when he stated that the 'greatest influence (of silviculture) on density is an indirect one arising from a shortening of the rotation'. The investigation reported here has shown that while on a whole tree basis juvenile wood is produced by every living tree every year, only trees actively growing in the butt log region produce mature wood. By keeping stand age constant and comparing values across a range of silviculture regimes the change in amount of mature wood produced, independent of rotation age effect, has been highlighted. This investigation stops short of ascribing values for fibre length, density or other intrinsic properties to the wood but the silvicultural parameter that has been developed is so obviously related to intrinsic properties that there can be little doubt about the general conclusions to be drawn from this work. Wood properties are clearly influenced by silviculture in a way not actively considered before. Of course, the range of regimes tested here is much broader than would be

considered for a single product objective. For example, if sawlogs were the objective then the range of tending schedules: from early thinning to 380 stems/ha, to 5000 stems/ha unthinned, far exceeds the likely choice, and the difference in production of mature-wood between these two extremes exaggerates the difference between viable regime alternatives. The first two regime groups in Table 12.3 do however illustrate very real alternatives. The first group (thinned early to 380/ha) represents a regime that would maximise growth on the crop trees and, for a given target diameter (in this case 48cm mean dbh (ob), see Fenton (1971)), result in a shortened rotation. The second group has the same product objective and stocking level but thinning was delayed in order to reduce branch sizes. As well as the additional time to achieve the target diameter, these results show that by three quarters of the rotation production of mature wood is 15% less and that additional time will also be necessary to achieve the same production of mature wood. It also indicates that as long as growth rates are high the wide bands of older wood in the butt log region may well compensate for the reduced age of clearfelling now occurring in New Zealand.

The precise effect of variation in volume of mature wood on the out-turn of sawn timber by strength grades cannot yet be calculated. However, the fact that even such a comparatively subtle variation in tending schedule can be detected as early as 17 years using the methods developed here, suggests that the effect of silviculture on intrinsic wood properties is important enough to consider when designing regimes or projecting the results of alternative regimes.

Where biomass or weight of wood is required, applying wood density values to volume subdivided into wood age categories will enable this to be determined.

The values presented in Table 12.3 are whole-of-tree values, differences between treatments are likely to be greatest in the most valuable bottom logs. The development of a model to predict mature-wood-volume for selected parts of the tree (butt log, upper logs etc.) is the first most logical extension of this work. Another obvious area where further work is possible is the diameter model. The current model could undoubtedly be improved and work toward such improvement would concentrate on removing the tendency to underestimate the growth of the largest trees and the mis-identification of mortality. This must raise the question of whether an individual tree model is the most appropriate for this work. Experience with this type of model has not been good, for example, as already cited from Alemdag (1978). Adlard (1974) also reports results from many sources where indices of tree competition (which are a fundamental part of individual tree models) 'have accounted for an unexpectedly small amount of variation beyond that associated with the previous growth history of the tree'. Both Tennant(1981) and Manley (1981) report biases among the models they investigated. A possible alternative approach is to use a stand level model to predict stocking and basal area and a distribution function to predict diameter distribution for the appropriate year.

If an individual tree model was retained, experience with the diameter growth model used here has shown that it is advisable to model more than one example of any regime to derive a general estimate for that regime. Because a regression based model predicts the average response to a given situation, the response may differ widely from the actual value. For any model which relies on repeated annual predictions and where the predicted value provides the starting point for the next projection, differences between predicted and actual values may increase with each successive estimate

The result can be a severe one or under estimate. Without actual values for comparison this effect will be undetectable. The risk can be obviated by basing predictions on at least three data sets.

The models presented here were derived from a very specialised data source. Only one site is represented and growth rates are very high. No pretence is made that the models have wide application. The advantage of using such a restricted data source is that all data was compatible and of high quality but most importantly many sources of variation were removed thus facilitating model development. The young age of the oldest measurements is a disadvantage although because of the high site index, 17 years represents about three quarters of the rotation. Although this is a disadvantage, it has not obscured the main results, indeed the differences between regimes of volume of mature wood found here can be expected to increase with increasing tree age.

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APPENDIX 1

EXAMPLES OF PREDICTIONS FOR INDIVIDUAL PLOTS

The computed results from the program TOTALMOD are given for three plots. Their details are:

Plot *	Regime *	Trees per Plot	Years Projected
9x3	T380-L.R.	23	7
9x9	T750	45	10
6x9	UT3000	150	11

* symbols as for table 8.10.

Plot 9x3

RESULTS OF MODEL --- BY TREE

TREE NUMBER	INITIAL DIAMETER	ACTUAL FINAL DIAMETER	PROJECTED FINAL DIAMETER	PROJECTED HEIGHT	PROJECTED VOLUME	PROJECTED MEAN WOOD AGE
1	0.193	0.259	0.256	28.9	0.543	6.369
2	0.224	0.311	0.324	32.2	0.973	7.076
3	0.221	0.291	0.310	32.2	0.893	6.962
4	0.241	0.378	0.385	31.3	1.342	7.474
5	0.218	0.396	0.430	34.1	1.829	7.916
6	0.193	0.357	0.391	30.8	1.361	7.481
7	0.244	0.434	0.435	30.7	1.687	7.735
8	0.218	0.360	0.385	31.7	1.359	7.496
9	0.193	0.330	0.339	30.9	1.026	7.144
10	0.175	0.236	0.238	25.5	0.410	6.117
11	0.229	0.383	0.363	31.1	1.186	7.322
12	0.234	0.389	0.380	33.6	1.405	7.560
13	0.196	0.300	0.344	34.7	1.185	7.330
14	0.213	0.334	0.391	32.3	1.433	7.571
15	0.251	0.388	0.376	30.4	1.244	7.368
16	0.246	0.450	0.371	31.0	1.234	7.368
17	0.257	0.348	0.384	33.4	1.424	7.576
18	0.236	0.361	0.371	29.9	1.194	7.312
19	0.183	0.295	0.233	27.6	0.426	6.096
20	0.213	0.363	0.349	31.3	1.099	7.230
21	0.274	0.413	0.415	31.8	1.585	7.687
22	0.218	0.350	0.370	29.5	1.166	7.276
23	0.267	0.405	0.393	33.0	1.478	7.620
		---	---		---	
	MEAN	0.354	MEAN 0.358	TOTAL	27.482	
	SDEV	0.054	SDEV 0.055			
	MORT	0	MORT 0			
	DMAX	0.450	D2MAX 0.435			
	DMIN	0.236	D2MIN 0.233			
			MS-R 0.000938			

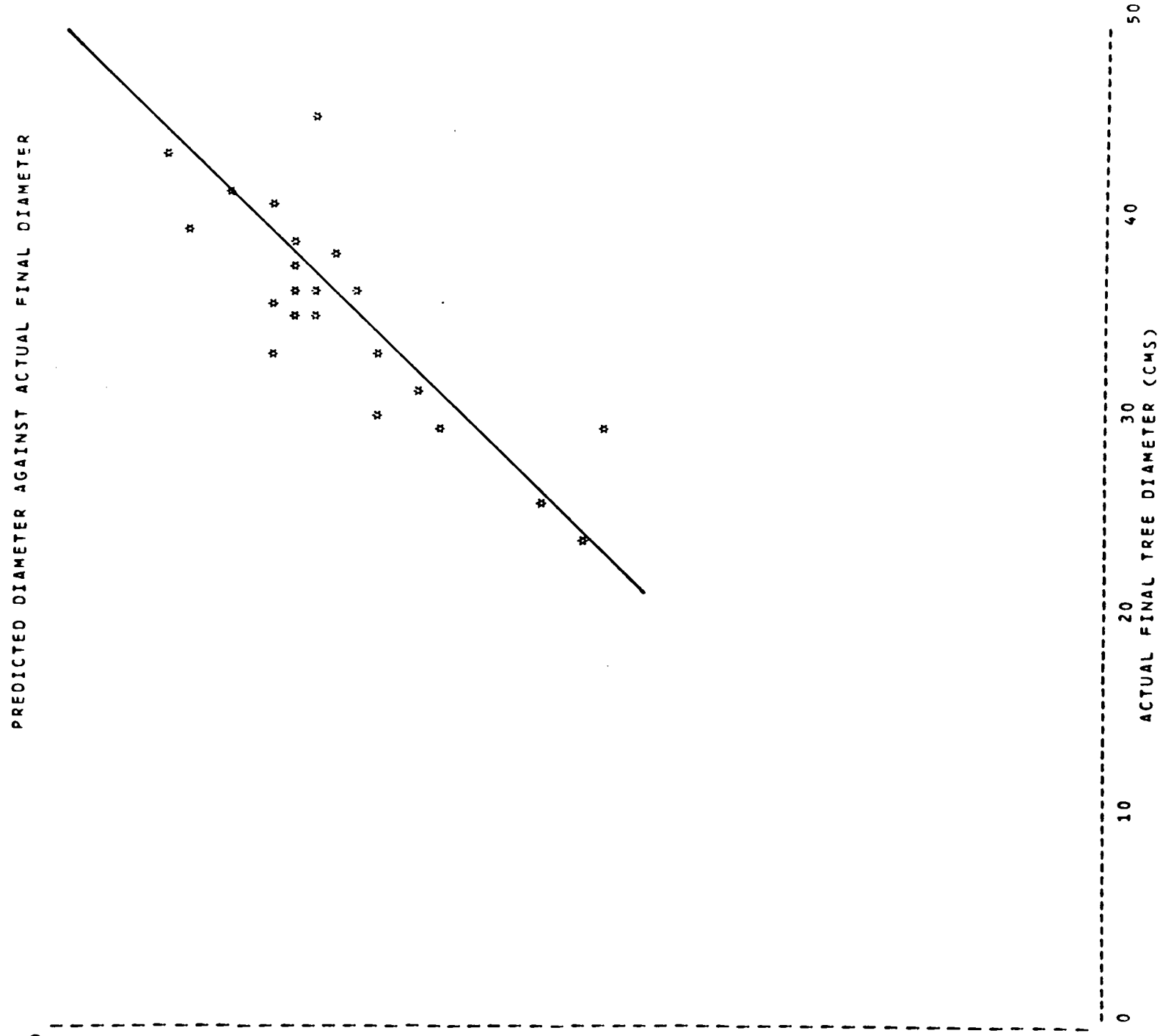
RESULTS OF MODEL --- FOR PLOT

AGE	VOLUME	PERCENT
0.5	0.3338	1.2
1.5	1.0058	3.7
2.5	1.6250	5.9
3.5	2.1378	7.8
4.5	2.5086	9.1
5.5	2.7199	9.9
6.5	2.7722	10.1
7.5	2.6821	9.8
8.5	2.4778	9.0
9.5	2.1943	8.0
10.5	1.8676	6.8
11.5	1.5305	5.6
12.5	1.2093	4.4
13.5	0.9221	3.4
14.5	0.6791	2.5
15.5	0.4833	1.8
16.5	0.3325	1.2

TOTAL	27.482	

MEAN WOOD-AGE 7.536

App.1


PREDICTED DIAMETER AGAINST ACTUAL FINAL DIAMETER
PREDICTED DIA (50CM)
ACTUAL FINAL TREE DIAMETER (CMS)
0
10
20
30
40
50

COMPARISON OF STAND DIAMETERS AT 17 YEARS

DIAMETER CLASS	ACTUAL		PREDICTED		INCREMENT CLASS	ACTUAL		PREDICTED	
CLASS	NO.	PERCENT	NO.	PERCENT	CLASS	NO.	PERCENT	NO.	PERCENT
0.000	0	0.0	0	0.0	0.0000	0	0.0	0	0.0
0.020	0	0.0	0	0.0	0.0008	0	0.0	0	0.0
0.040	0	0.0	0	0.0	0.0016	0	0.0	1	4.3
0.060	0	0.0	0	0.0	0.0024	1	4.3	2	8.7
0.080	0	0.0	0	0.0	0.0032	1	4.3	0	0.0
0.100	0	0.0	0	0.0	0.0040	1	4.3	0	0.0
0.120	0	0.0	0	0.0	0.0048	1	4.3	1	4.3
0.140	0	0.0	0	0.0	0.0056	3	13.0	1	4.3
0.160	0	0.0	0	0.0	0.0064	0	0.0	0	0.0
0.180	0	0.0	0	0.0	0.0072	1	4.3	0	0.0
0.200	0	0.0	0	0.0	0.0080	3	13.0	3	13.0
0.220	1	4.3	2	8.7	0.0088	2	8.7	6	26.1
0.240	1	4.3	1	4.3	0.0096	3	13.0	3	13.0
0.260	0	0.0	0	0.0	0.0104	4	17.4	1	4.3
0.280	3	13.0	0	0.0	0.0112	0	0.0	1	4.3
0.300	1	4.3	1	4.3	0.0120	1	4.3	1	4.3
0.320	2	8.7	2	8.7	0.0128	0	0.0	1	4.3
0.340	4	17.4	2	8.7	0.0136	0	0.0	0	0.0
0.360	3	13.0	5	21.7	0.0144	1	4.3	1	4.3
0.380	4	17.4	7	30.4	0.0152	1	4.3	1	4.3
0.400	2	8.7	1	4.3	0.0160	0	0.0	0	0.0
0.420	1	4.3	2	8.7	0.0168	0	0.0	0	0.0
0.440	1	4.3	0	0.0	0.0176	0	0.0	0	0.0
0.460	0	0.0	0	0.0	0.0184	0	0.0	0	0.0
0.480	0	0.0	0	0.0	0.0192	0	0.0	0	0.0
0.500	0	0.0	0	0.0	0.0200	0	0.0	0	0.0

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Plot 9x9

RESULTS OF MODEL --- BY TREE

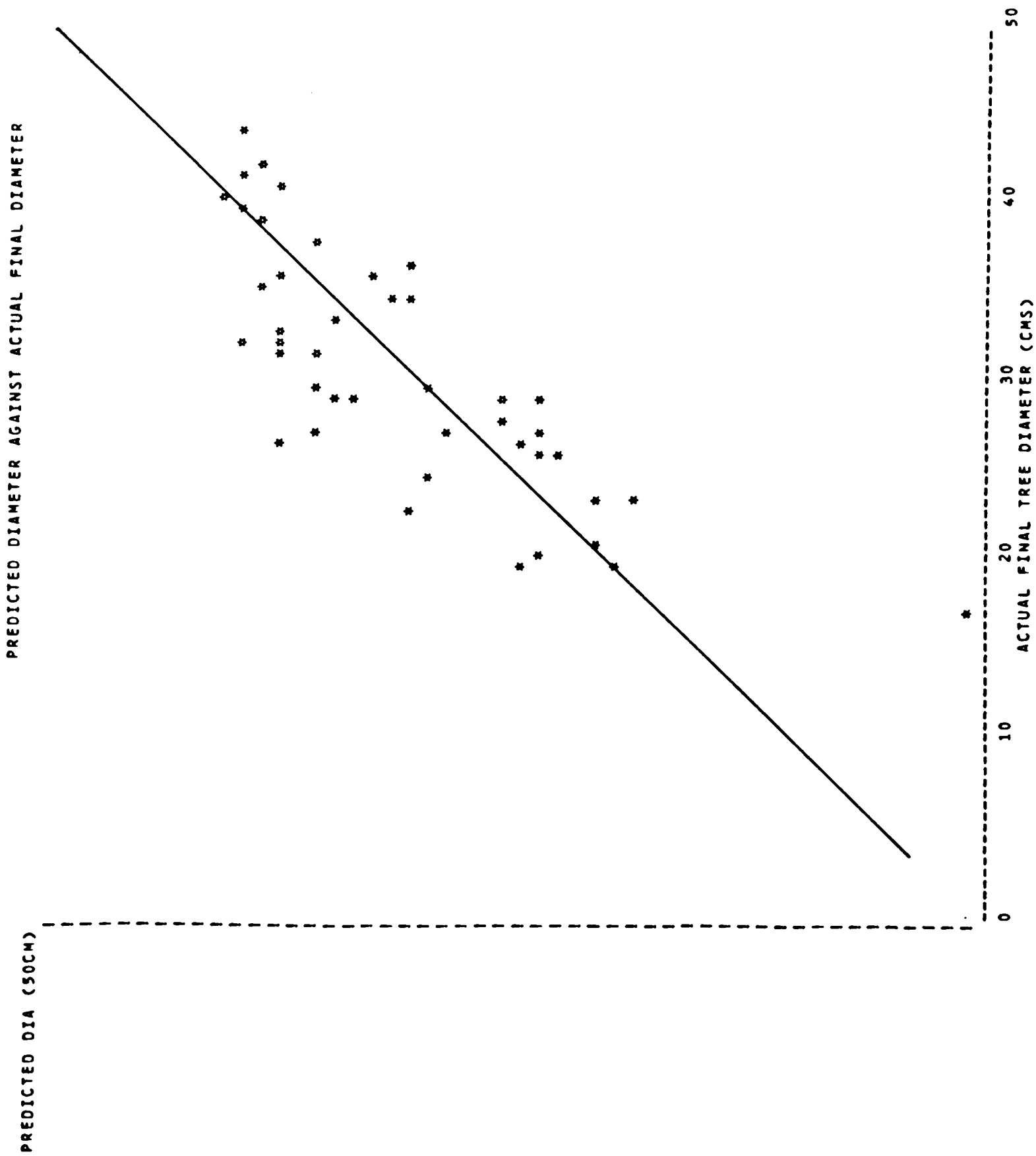
TREE NUMBER	INITIAL DIAMETER	ACTUAL FINAL DIAMETER	PROJECTED FINAL DIAMETER	PROJECTED HEIGHT	PROJECTED VOLUME	PROJECTED MEAN WOOD AGE
1	0.175	0.342	0.308	30.7	0.839	6.895
2	0.180	0.271	0.352	32.7	1.171	7.317
3	0.175	0.322	0.370	33.5	1.328	7.485
4	0.157	0.191	0.238	27.3	0.442	6.155
5	0.152	0.288	0.229	28.8	0.431	6.062
6	0.142	0.195	0.192	23.9	0.247	5.581
7	0.165	0.271	0.276	27.9	0.608	6.529
8	0.140	0.233	0.179	23.1	0.205	5.395
9	0.203	0.314	0.353	31.2	1.124	7.257
10	0.224	0.392	0.390	29.3	1.287	7.383
11	0.160	0.362	0.296	29.7	0.748	6.760
12	0.147	0.258	0.222	28.4	0.400	5.974
13	0.155	0.287	0.254	31.7	0.589	6.386
14	0.114	0.166	0.000	0.0	0.000	0.000
15	0.193	0.355	0.321	31.1	0.926	7.017
16	0.203	0.333	0.337	29.8	0.978	7.079
17	0.183	0.265	0.370	30.9	1.223	7.356
18	0.196	0.319	0.389	33.5	1.465	7.614
19	0.213	0.352	0.380	30.0	1.253	7.369
20	0.201	0.418	0.376	31.8	1.306	7.449
21	0.198	0.332	0.340	31.1	1.038	7.159
22	0.165	0.291	0.289	29.5	0.707	6.692
23	0.208	0.439	0.393	29.8	1.330	7.432
24	0.147	0.273	0.251	29.3	0.527	6.318
25	0.185	0.269	0.350	31.8	1.127	7.264
26	0.188	0.285	0.337	30.1	0.986	7.091
27	0.163	0.258	0.228	29.5	0.438	6.047
28	0.173	0.222	0.300	30.3	0.786	6.816
29	0.196	0.356	0.371	31.8	1.265	7.409
30	0.155	0.372	0.349	31.5	1.113	7.247
31	0.206	0.318	0.373	31.6	1.273	7.414
32	0.160	0.346	0.297	30.1	0.766	6.785
33	0.132	0.232	0.200	26.7	0.301	5.666
34	0.208	0.415	0.387	31.9	1.381	7.518
35	0.155	0.245	0.289	28.1	0.675	6.648
36	0.140	0.267	0.225	26.7	0.385	6.002
37	0.216	0.385	0.382	33.7	1.420	7.575
38	0.201	0.291	0.353	29.1	1.047	7.148
39	0.201	0.406	0.374	29.4	1.191	7.299
40	0.150	0.203	0.231	27.2	0.412	6.070
41	0.147	0.260	0.241	25.5	0.424	6.152
42	0.170	0.285	0.333	31.2	0.999	7.111
43	0.196	0.313	0.375	31.8	1.292	7.434
44	0.140	0.207	0.201	25.2	0.288	5.697
45	0.224	0.403	0.403	29.3	1.380	7.461
		---	---		---	
MEAN		0.302	0.311	TOTAL	39.118	
SDEV		0.067	0.067			
MORT		0	1			
DMAX		0.439	D2MAX 0.403			
DMIN		0.166	D2MIN 0.000			

RESULTS OF MODEL --- FOR PLOT

AGE	VOLUME	PERCENT
0.5	0.6157	1.6
1.5	1.7078	4.4
2.5	2.6255	6.7
3.5	3.3261	8.5
4.5	3.7806	9.7
5.5	3.9852	10.2
6.5	3.9602	10.1
7.5	3.7442	9.6
8.5	3.3874	8.7
9.5	2.9435	7.5
10.5	2.4631	6.3
11.5	1.9885	5.1
12.5	1.5507	4.0
13.5	1.1695	3.0
14.5	0.8535	2.2
15.5	0.6032	1.5
16.5	0.4130	1.1
TOTAL	39.118	

MEAN WOOD-AGE 7.235

App. 1


PREDICTED DIAMETER AGAINST ACTUAL FINAL DIAMETER
PREDICTED DIA (50CM)
ACTUAL FINAL TREE DIAMETER (CMS)
0
10
20
30
40
50

COMPARISON OF STAND DIAMETERS AT 17 YEARS

DIAMETER CLASS	ACTUAL		PREDICTED		INCREMENT CLASS	ACTUAL		PREDICTED	
CLASS	NO.	PERCENT	NO.	PERCENT	CLASS	NO.	PERCENT	NO.	PERCENT
0.000	0	0.0	1	2.2	0.0000	0	0.0	1	2.2
0.020	0	0.0	0	0.0	0.0008	5	11.1	2	4.4
0.040	0	0.0	0	0.0	0.0016	1	2.2	5	11.1
0.060	0	0.0	0	0.0	0.0024	6	13.3	5	11.1
0.080	0	0.0	0	0.0	0.0032	6	13.3	2	4.4
0.100	0	0.0	0	0.0	0.0040	9	20.0	3	6.7
0.120	0	0.0	0	0.0	0.0048	3	6.7	4	8.9
0.140	0	0.0	0	0.0	0.0056	2	4.4	3	6.7
0.160	1	2.2	1	2.2	0.0064	3	6.7	5	11.1
0.180	2	4.4	2	4.4	0.0072	2	4.4	8	17.8
0.200	2	4.4	1	2.2	0.0080	2	4.4	5	11.1
0.220	3	6.7	6	13.3	0.0088	2	4.4	2	4.4
0.240	4	8.9	3	6.7	0.0096	2	4.4	0	0.0
0.260	6	13.3	1	2.2	0.0104	1	2.2	0	0.0
0.280	6	13.3	4	8.9	0.0112	1	2.2	0	0.0
0.300	4	8.9	2	4.4	0.0120	0	0.0	0	0.0
0.320	3	6.7	5	11.1	0.0128	0	0.0	0	0.0
0.340	5	11.1	5	11.1	0.0136	0	0.0	0	0.0
0.360	2	4.4	8	17.8	0.0144	0	0.0	0	0.0
0.380	2	4.4	5	11.1	0.0152	0	0.0	0	0.0
0.400	4	8.9	1	2.2	0.0160	0	0.0	0	0.0
0.420	1	2.2	0	0.0	0.0168	0	0.0	0	0.0
0.440	0	0.0	0	0.0	0.0176	0	0.0	0	0.0
0.460	0	0.0	0	0.0	0.0184	0	0.0	0	0.0
0.480	0	0.0	0	0.0	0.0192	0	0.0	0	0.0
0.500	0	0.0	0	0.0	0.0200	0	0.0	0	0.0

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Plot 6x9

RESULTS OF MODEL --- BY TREE

TREE NUMBER	INITIAL DIAMETER	ACTUAL FINAL DIAMETER	PROJECTED FINAL DIAMETER	PROJECTED HEIGHT	PROJECTED VOLUME	PROJECTED MEAN WOOD SG
1	0.160	0.232	0.268	29.4	0.607	6.501
2	0.137	0.146	0.215	27.6	0.364	5.882
3	0.135	0.152	0.194	26.3	0.278	5.579
4	0.152	0.211	0.242	27.5	0.460	6.200
5	0.137	0.000	0.198	26.6	0.295	5.644
6	0.155	0.262	0.277	28.4	0.626	6.557
7	0.124	0.141	0.160	19.5	0.136	5.174
8	0.122	0.146	0.154	20.4	0.131	5.057
9	0.135	0.179	0.192	24.6	0.253	5.569
10	0.152	0.190	0.262	26.5	0.521	6.367
11	0.163	0.272	0.268	28.8	0.595	6.489
12	0.091	0.132	0.000	0.0	0.000	0.000
13	0.135	0.000	0.210	27.5	0.343	5.804
14	0.180	0.233	0.327	34.3	1.058	7.173
15	0.114	0.139	0.000	0.0	0.000	0.000
16	0.124	0.151	0.158	20.8	0.140	5.108
17	0.157	0.331	0.278	28.3	0.629	6.565
18	0.117	0.130	0.000	0.0	0.000	0.000
19	0.180	0.211	0.329	30.2	0.944	7.040
20	0.170	0.303	0.325	32.3	0.984	7.091
21	0.130	0.158	0.167	20.9	0.159	5.247
22	0.168	0.000	0.306	30.5	0.821	6.870
23	0.147	0.208	0.247	28.2	0.493	6.265
24	0.142	0.248	0.207	25.6	0.311	5.779
25	0.142	0.176	0.222	25.0	0.350	5.948
26	0.130	0.165	0.163	21.2	0.153	5.181
27	0.137	0.152	0.204	26.0	0.306	5.735
28	0.155	0.227	0.250	27.5	0.493	6.285
29	0.127	0.183	0.000	0.0	0.000	0.000
30	0.180	0.308	0.330	33.5	1.053	7.173
31	0.163	0.193	0.258	28.8	0.551	6.392
32	0.124	0.132	0.155	20.6	0.133	5.064
33	0.102	0.133	0.000	0.0	0.000	0.000
34	0.145	0.277	0.241	28.1	0.468	6.200
35	0.157	0.000	0.275	29.3	0.637	6.565
36	0.137	0.186	0.216	26.5	0.351	5.890
37	0.142	0.300	0.241	29.5	0.491	6.216
38	0.119	0.143	0.168	22.6	0.176	5.241
39	0.119	0.000	0.191	23.2	0.237	5.567
40	0.132	0.191	0.187	23.9	0.233	5.502
41	0.160	0.307	0.299	31.9	0.823	6.856
42	0.155	0.000	0.260	26.7	0.517	6.356
43	0.147	0.278	0.216	24.6	0.326	5.881
44	0.165	0.231	0.294	29.8	0.744	6.752
45	0.079	0.000	0.000	0.0	0.000	0.000
46	0.051	0.000	0.000	0.0	0.000	0.000
47	0.089	0.000	0.000	0.0	0.000	0.000
48	0.112	0.158	0.000	0.0	0.000	0.000
49	0.127	0.159	0.167	20.5	0.156	5.255
50	0.097	0.098	0.000	0.0	0.000	0.000
51	0.137	0.202	0.196	25.3	0.273	5.624
52	0.147	0.194	0.232	27.5	0.420	6.084
53	0.130	0.000	0.192	24.5	0.254	5.575

App. 1

| | | |

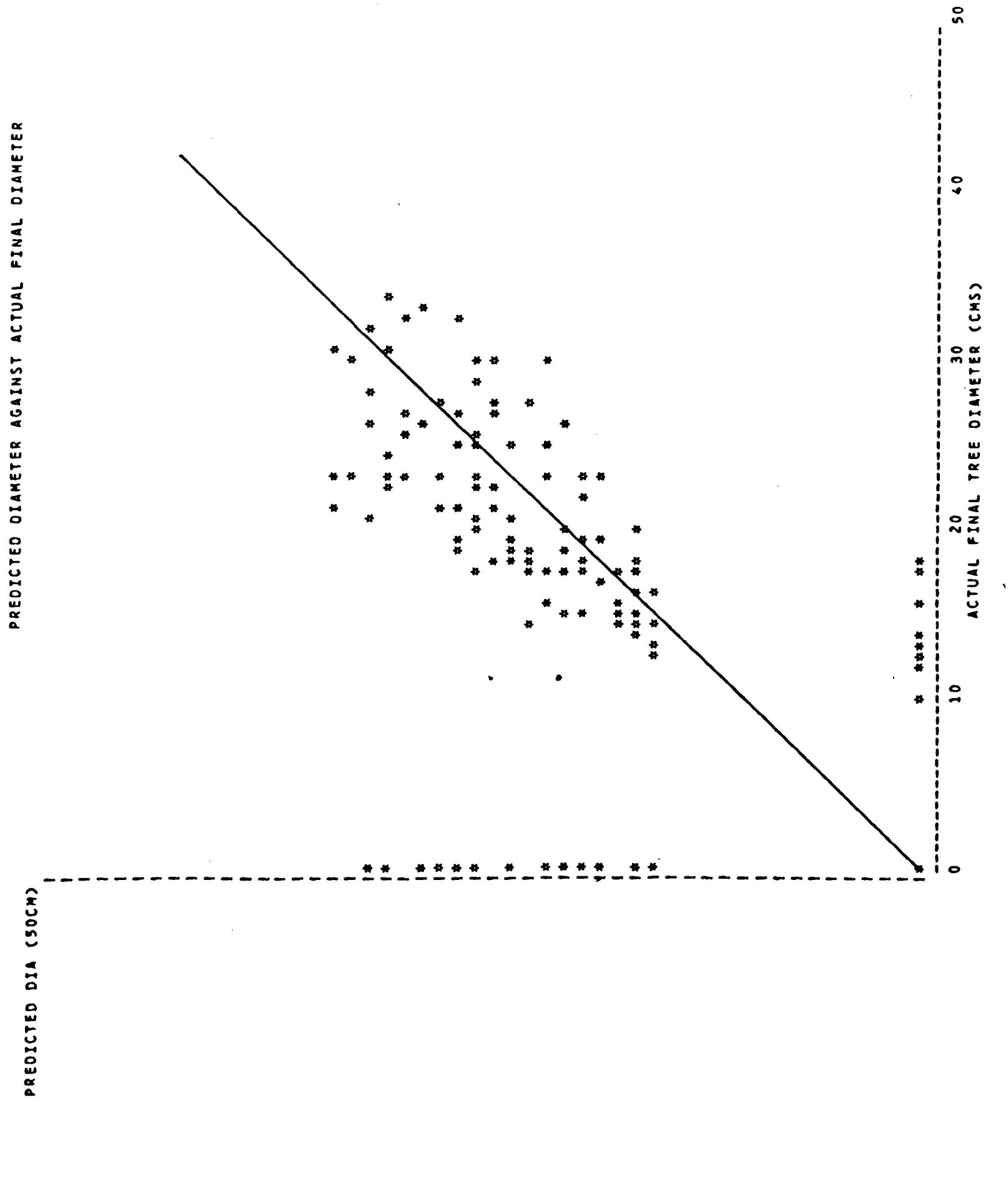
116	0.117	0.000	0.147	21.1	0.124	4.913
117	0.130	0.172	0.192	25.0	0.259	5.576
118	0.150	0.000	0.272	30.3	0.644	6.559
119	0.152	0.202	0.247	27.5	0.479	6.251
120	0.152	0.226	0.243	27.2	0.458	6.200
121	0.147	0.184	0.231	27.2	0.415	6.078
122	0.137	0.177	0.214	27.2	0.354	5.865
123	0.124	0.176	0.157	20.2	0.136	5.120
124	0.137	0.175	0.187	25.0	0.246	5.500
125	0.160	0.269	0.264	28.2	0.562	6.429
126	0.091	0.000	0.000	0.0	0.000	0.000
127	0.135	0.196	0.188	25.2	0.249	5.508
128	0.168	0.282	0.307	31.5	0.854	6.911
129	0.132	0.156	0.166	22.4	0.170	5.214
130	0.109	0.000	0.000	0.0	0.000	0.000
131	0.127	0.173	0.173	24.2	0.202	5.284
132	0.102	0.000	0.000	0.0	0.000	0.000
133	0.160	0.328	0.263	28.2	0.557	6.419
134	0.122	0.000	0.164	20.2	0.148	5.215
135	0.142	0.302	0.211	27.0	0.341	5.825
136	0.163	0.324	0.294	28.2	0.702	6.693
137	0.140	0.184	0.224	25.8	0.367	5.975
138	0.127	0.183	0.163	20.8	0.152	5.199
139	0.160	0.243	0.297	31.6	0.805	6.832
140	0.117	0.138	0.000	0.0	0.000	0.000
141	0.152	0.234	0.247	28.7	0.500	6.268
142	0.152	0.255	0.252	29.4	0.533	6.331
143	0.155	0.211	0.263	27.2	0.541	6.401
144	0.142	0.187	0.228	26.1	0.384	6.024
145	0.086	0.000	0.000	0.0	0.000	0.000
146	0.165	0.338	0.300	27.5	0.714	6.710
147	0.140	0.000	0.214	26.8	0.348	5.862
148	0.152	0.233	0.299	29.9	0.772	6.797
149	0.140	0.183	0.244	26.6	0.452	6.201
150	0.145	0.250	0.251	27.9	0.503	6.299
		---	---		---	
	MEAN	0.205	MEAN 0.229	TOTAL	50.076	
	SDEV	0.056	SDEV 0.050			
	MORT	37	MORT 34			
	DMAX	0.338	D2MAX 0.330			
	DMIN	0.000	D2MIN 0.000			
			MS-R 0.010079			

RESULTS OF MODEL --- FOR PLOT

AGE	VOLUME	PERCENT
0.5	1.3084	2.6
1.5	3.1486	6.3
2.5	4.4047	8.8
3.5	5.1628	10.3
4.5	5.4715	10.9
5.5	5.4029	10.8
6.5	5.0471	10.1
7.5	4.4998	9.0
8.5	3.8508	7.7
9.5	3.1753	6.3
10.5	2.5298	5.1
11.5	1.9514	3.9
12.5	1.4596	2.9
13.5	1.0599	2.1
14.5	0.7479	1.5
15.5	0.5132	1.0
16.5	0.3427	0.7
TOTAL	50.076	

MEAN WOOD-AGE 6.475

App. 1


PREDICTED DIAMETER AGAINST ACTUAL FINAL DIAMETER
PREDICTED DIA (SOCM)
ACTUAL FINAL TREE DIAMETER (CMS)
0
10
20
30
40
50

COMPARISON OF STAND DIAMETERS AT 17 YEARS

DIAMETER CLASS	ACTUAL		PREDICTED		INCREMENT CLASS	ACTUAL		PREDICTED	
CLASS	NO.	PERCENT	NO.	PERCENT	CLASS	NO.	PERCENT	NO.	PERCENT
0.000	37	24.7	34	22.7	0.0000	70	46.7	49	32.7
0.020	0	0.0	0	0.0	0.0008	38	25.3	29	19.3
0.040	0	0.0	0	0.0	0.0016	12	8.0	20	13.3
0.060	0	0.0	0	0.0	0.0024	10	6.7	22	14.7
0.080	1	0.7	0	0.0	0.0032	8	5.3	9	6.0
0.100	2	1.3	0	0.0	0.0040	4	2.7	13	8.7
0.120	11	7.3	0	0.0	0.0048	5	3.3	8	5.3
0.140	14	9.3	8	5.3	0.0056	3	2.0	0	0.0
0.160	17	11.3	12	8.0	0.0064	0	0.0	0	0.0
0.180	15	10.0	22	14.7	0.0072	0	0.0	0	0.0
0.200	12	8.0	14	9.3	0.0080	0	0.0	0	0.0
0.220	12	8.0	9	6.0	0.0088	0	0.0	0	0.0
0.240	7	4.7	18	12.0	0.0096	0	0.0	0	0.0
0.260	9	6.0	12	8.0	0.0104	0	0.0	0	0.0
0.280	4	2.7	9	6.0	0.0112	0	0.0	0	0.0
0.300	5	3.3	7	4.7	0.0120	0	0.0	0	0.0
0.320	4	2.7	5	3.3	0.0128	0	0.0	0	0.0
0.340	0	0.0	0	0.0	0.0136	0	0.0	0	0.0
0.360	0	0.0	0	0.0	0.0144	0	0.0	0	0.0
0.380	0	0.0	0	0.0	0.0152	0	0.0	0	0.0
0.400	0	0.0	0	0.0	0.0160	0	0.0	0	0.0
0.420	0	0.0	0	0.0	0.0168	0	0.0	0	0.0
0.440	0	0.0	0	0.0	0.0176	0	0.0	0	0.0
0.460	0	0.0	0	0.0	0.0184	0	0.0	0	0.0
0.480	0	0.0	0	0.0	0.0192	0	0.0	0	0.0
0.500	0	0.0	0	0.0	0.0200	0	0.0	0	0.0

D OF LISTING OF FILE :SYSTEX.ICL9NSPOOLLIB(4,ICLS,1).ICL8307131227009900(1) FOR USER :RYDE AT 1983/07/13__12:30:48

****

APPENDIX 2

DESCRIPTION OF STATISTICAL PACKAGES

Program NONLIN

This program is one of a suite of statistical programs available to computer users at Oxford University, within the Forestry User Group. The program fits one linear and 11 non-linear regression curves of the general form $y = f(bx)$, to a set of paired observations: $y_1 \ldots\ldots y_n$, $x_1 \ldots\ldots x_n$. The non-linear models are fitted by an interative procedure where, for each model in turn coefficients are supplied by the program and the model tested with the data set. Initial values for parameters are estimated by transforming the equation to linear form, by using logs or by differentiating, and solving by least squares methods.

The criterion for goodness of fit is the squared deviation of actual from predicted values. The program aims to minimize the sum of squared residuals and contains a procedure to determine whether further alteration to the coefficients will result in a significant reduction in the value of the squared residuals. If the model being tested is suitable for the data-set, the program will usually find a stable solution within 30 interations. The criterion for initial choice of the most appropriate model is the coefficient of determination (r^2).

The models tested by the NONLIN program are:

$$y = a + bx$$

$$y = a + b/x$$

$$y = a + bx + cx^2$$

$$y = a + be^{-cx}$$

$$y = a(1-e^{bx})$$

$y = a + bx^c$

$y = ax^b$

$y = 1/(a+bx)$

$y = x/(a+bx)$

$y = 1/(a+be^{-cx})$

$y = a(1-e^{bx})^c$

$y = x/(a+bx+cx^2)$

The program plots the calculated curve and the data. Attempts to fit models are abandoned after if no stable solution is attained after 30 iterations or if after 30 iterations the sum of squared deviations is greater than the sum of squared deviations about the mean.

Program ANDRESS

This program calculates multiple linear regressions for a number of independent variables on a given dependant variable. The variable can be transformed, weighted on interactions derived by all the common arithmetic operations plus; square root, logarithm, arc sine and linear transformations. The program has the facility for developing the regression in a step-wise fashion, eliminating non-significant variables one at a time. Output includes means and standard deviations of all variables and their variance-covariance matrix. The estimated regression coefficients are given with their standard errors and statistical significance. An analysis of variance is given for the regression. The program is contained in the Forestry 'STATS' package.

Program C.G.M.P.

This program is essentially similar to ANDRESS and performs the same calculations (i.e. step-wise multiple regression analysis) with similar output.

It differs chiefly in having very comprehensive graphical output. A scatter diagram can be drawn showing the relationship of any variable, transformed or otherwise, to any other variable. this facility is especially useful when comparing the distribution of residual deviation. When deviation (Actual value-predicted value) is plotted against actual value, the reliability of the model as a predictive tool can be assessed. For example it can be seen whether or not error is evenly distributed for all values of the dependant variable. By plotting residual deviation against independent variables, possible sources of bias are indicated. Another useful feature of this program, not present in ANDRESS is the 'flag' command which enables the data to be partitioned or unrealistic transformations to be eliminated. As with the other programs, CGMP is part of the STATS suite.

Program VOLTAB

This is the standard Oxford Forestry Department volume table program. As with the others it is part of the STATS suite of programs. In its method of operation it is a combination of NONLIN and the multiple regression packages. Data for volume, d.b.h. and height are entered untransformed, the program then attempts to fit 15 likely multiple regression models in turn. The transformations necessary for the various models being performed by the program without the need for user intervention. As many of the models solve for transformations of volume, models are compared by the Furnival Index (previously described) rather than by the coefficient of determination (r^2). The models tested are (in generalised form):

$$V = D$$

$$V = D + D^2$$

$$V = D^2$$

$V = D^2 H$

$V = D^2 + H + D^2 H$

$V = D^2 + DH + D^2 H$

$\text{Log } V = \text{Log } D$

$\text{Log } V = \text{Log } D + \text{Log } H$

$V = D + D^2$ weighted by D^2

$V = D^2$ weighted by D^2

$V = D^2 H$ weighted by $D^2 H$

$V = D^2 + H + D^2 H$ weighted by D^2

$V = D^2 + H + D^2 H$ weighted by $D^2 H$

$V = D^2 + DH + D^2 H$ weighted by D^2

$V = D^2 + DH + D^2 H$ weighted by $D^2 H$

where V is a measure of volume

D is a measure of diameter

and H is a measure of height

For the investigation presented here volume was in cubic metres to a 10cm top, diameter was dbh(ob) in metres, and height was total tree height in metres.

APPENDIX 3

DESCRIPTION AND COPY OF TOTALMOD

It is considered more appropriate for this program to give the description in text rather than as a flow chart.

Although the program could easily be altered to consider the general case, in its present form calculations are performed on the assumption that the data refer to a plot of size 0.0607ha and that the last set of diameter measurements was for trees aged 17 years. Data is supplied from two main files, one for diameter data the other for location data and two subsidiary computer files with control information.

The program first reads the number of annual measurement records and whether or not the plot has been thinned. From one of the main files, the number of trees in the plot and their mapped co-ordinates are read. From the same file the number of trees in the 'buffer' or between-plots zone and their coordinates and diameters are read. From the second main file the diameter data are read as a two dimensional array where the number of columns is equal to the number of annual measurements available and the number of rows is equal to the number of trees in the plot. A control variable is created to control the number of sub-routine calls and the number of tree deaths is set at zero.

The sub-routine CHANGE is called. This is the main routine for the program and the one in which the major calculations are performed. The increment period (i.e. 1st, 2nd etc.) is advanced by one and stocking (trees/plot) adjusted for deaths occurring in the previous increment period. On the first call of this sub-routine the second minor file is consulted to see if information on non-competitive mortality has been supplied.

The routine then enters a large loop where operations are performed once for every tree. If the tree under consideration is alive the coordinates of all the other trees are changed so that the origin is shifted from the plot centre to the location of the subject tree. The radius of the competition catchment is calculated as a function of plot stocking level and all trees tested to see if they are closer to the subject tree than this radius. If trees are within the competition catchment and alive (this is checked) they are listed as potential competitors and allocated to quartiles (i.e. 90° segments). This is repeated for trees in the 'buffer'. Trees from the two possible sources of competitors are combined in four lists (one per quartile) and the closest two per quartile determined. The sum of the competing basal area is determined by summing the basal area of the two closest trees per quartile. If competing trees are situated in the buffer their diameter is obtained by applying a growth model. (This was described in detail in the main text.) The competition index is the sum of competing basal area divided by the basal area of the subject tree. Other primary explanatory variables such as age and mean distance to competitors are calculated; then secondary variables (i.e. interactions). The increment of the tree is then calculated by the routine of one discriminator equation and three equations for each increment group, as described earlier. The basal area for the end of the period is derived and a short routine slightly increases the size of the largest few trees and slightly decreases the size of smallest few trees. Height is then predicted from diameter and age by the model described earlier. Finally, tree volume is predicted, again by a model described in the main text. Control is then returned to the beginning of the loop and the same sequence of calculations repeated for the next tree in the plot. Tree mortality is calculated as a function of increment. If it occurs the number of tree deaths is increased.

After the annual increment has been calculated for each tree and a new tree size calculated, control is returned to the master segment. If tree age is less than 17 years the sub-routine CHANGE is called again.

At tree age 17 years another subroutine called PRINT is called. The main purpose of this subroutine is to print out the results and comparisons with actual diameter values at 17 years.

First mean wood age is predicted for each tree using the multiple regression equation given in the text. Then the results are given for each tree in the plot: initial diameter, actual and projected final diameter, then predicted height, volume and mean wood age. Total volume per plot is calculated by summing individual tree volume and comparisons made between the actual and predicted diameter distributions. The distribution of volume by wood age is calculated for each tree in turn and summed to give a distribution for the plot. This is done using the Weibull distribution function. Because of error associated with the distribution function the stand total volume as distributed will be very slightly different from the volume obtained by totalling individual tree volumes - the distributed volume is adjusted so the two are equal and results are printed. Actual and predicted values for d.b.h.(ob) at 17 years are then presented graphically. This ends the operations of subroutine PRINT.

A further subroutine TEST is called. This routine calculates frequency distributions for actual and predicted diameter values and actual and predicted average annual increments in basal area. Results are printed in tabular form. The program then ends.

Another version called TIMEMOD has also been written where results and comparisons are given for every year of the period of prediction and not just at age 17 years.

```
      PROGRAM TOTALMOD
C THIS PROGRAM CALCULATES FOR EACH TREE IN PLOT,ITS COMPETITION
C CATCHMENT, IT SELECTS THE NEAREST TWO TREES (AS COMPETITORS)
C  PER QUARTILE, AND FOR EACH YEAR, IT CALCULATES:
C THE SUM COMPETING BA MEAN DIST TO COMPETITORS
C  & AGE; AND USES THESE TO CALCULATE INCREMENT
C THE PROGRAMME PERFORMS THE CALCULATIONS ONE PLOT AT A TIME
C (N.B. COMPETITORS/QUARTILE SET AT 2, SEE VARIABLE K19, C. LINE 210)
C AS MODEL IS FOR TARAWERA TRIAL IT ASSUMES PLOT=0.0607HA, MAX AGE =17
C
C
C THIS VERSION WILL ACCEPT SUPPLIED MORTALITY INFORMATION
C
C  AFTER FUTURE DIAMETER IS PREDICTED, HEIGHT IS ESTIMATED, (WITH
C  STOCHASTIC VARIATION), THEN VOLUME TO 10CM, THEN MEAN WOOD-AGE FOR EACH
C  TREE. FINALLY THE DISTRIBUTION OF WOOD BY WOODAGE IS ESTIMATED FOR EACH
C  TREE AND TOTALED FOR THE PLOT. MEAN WOOD-AGE IS CALCULATED ON A PLOT
C  (I.E. REGIME) BASIS.
      COMMON DIA(400,15),CORDX(400),CORDY(400)
      COMMON OUTX(300),OUTY(300),N,NTRE,M
      COMMON CHUTX(300),CHUTY(300),MEASNO,CHANX(400),CHANY(400)
      COMMON DOUT(300),NOUT,ICOUNT,BA(400,15)
      COMMON N1,THIN,D2(400,15),IDEATH,HT(400,15),VOL(400,15)
C READ NUMBER OF MEASUREMENTS AND WHETHER THINNING HAS OCCURRED
      READ(3,5)MEASNO,THIN
    5 FORMAT(I3,F4.1)
C READ IN TREE CO ORDS FOR PLOT TREES
      READ(5,105)NTRE
  105 FORMAT(I4)
      DO 101 I9=1,NTRE
      READ(5,13)CORDX(I9),CORDY(I9)
   13 FORMAT(2F6.2)
  101 CONTINUE
C READ CO ORDS AND DIA FOR OUT OF PLOT TREES
      READ(5,16)NOUT
   16 FORMAT(I4)
      DO 104 I3 =1,NOUT
      READ(5,17)OUTX(I3),OUTY(I3),DOUT(I3)
   17 FORMAT(2F6.2,F4.3)
  104 CONTINUE
C READ DIAMETERS FOR TREES WITHIN PLOT
      DO 100 I1=1,NTRE
      READ(6,12)(DIA(I1,I2),I2=1,MEASNO)
   12 FORMAT(F4.3,15F5.3)
  100 CONTINUE
      M=0
      DO 805 L5=1,NTRE
      BA(L5,1)=((DIA(L5,1)/2)**2)*3.1416
  805 CONTINUE
      CONTROL=MEASNO-1
      ICOUNT=NTRE
      IDEATH=0
  499 CALLCHANGE
      IF(M.LT.CONTROL) GOTO 499
      CALL PRINT
      CALL TEST
      STOP
      END
      SUBROUTINE CHANGE
      REAL G05DDF ,LEN1,LEN2,LEN3,LEN4
      INTEGER CAPT,CAP0,CAP1,CAP2,CAP3,CAP4,CAP01,CAP02,CAP03,CAP04
```

```
      INTEGER TCAP,AGE
      COMMON DIA(400,15),CORDX(400),CORDY(400)
      COMMON OUTX(300),OUTY(300),N,NTRE,M
      COMMON CHUTX(300),CHUTY(300),MEASNO,CHANX(400),CHANY(400)
      COMMON DOUT(300),NOUT,ICOUNT,BA(400,15)
      COMMON N1,THIN,D2(400,15),IDEATH,HT(400,15),VOL(400,15)
      DIMENSION CAPT(200),CAP1(50),CAP2(50),CAP3(50),CAP4(50),CAPO(200)
      DIMENSION CAPO1(50),CAPO2(50),CAPO3(50),CAPO4(50)
      DIMENSION FAR1(50),FAR2(50),FAR3(50),FAR4(50),LEN1(50),LEN2(56)
      DIMENSION LEN3(50),LEN4(50),LIST(10),COM1(100),COM2(100),COM3(100)
      DIMENSION COM4(100),ITREE(200),ITIME(200)
C CHANGE CO ORDS OF TREES SO THAT TARGET TREE IS AT ORIGIN
      M=M+1
      ICOUNT=ICOUNT-IDEATH
      IDEATH=0
      CALL G05CBF(0)
C CHECK FOR SUPPLIED MORTALITY (IE NON-COMPETITIVE MORTALITY)
      IF(M.GT.1) GOTO 986
      READ(4,988)IFATAL
      IF(IFATAL.EQ.0) GOTO 986
  988 FORMAT(I4)
      DO 985 L20=1,IFATAL
      READ(4,989)ITREE(L20),ITIME(L20)
  989 FORMAT(2I4)
  985 CONTINUE
  986 DO 153 N=1,NTRE
      IF(IFATAL.EQ.0) GOTO 987
      DO 1000 L21=1,IFATAL
      IF(ITREE(L21).NE.N) GOTO 1000
      IF(ITIME(L21).NE.M) GOTO 1000
      BA(N,M)=0.0
      IDEATH=IDEATH+1
      GOTO 987
 1000 CONTINUE
  987 IF(BA(N,M).EQ.0.0) BA(N,(M+1))=0.0
      IF(BA(N,M).EQ.0.0) GOTO 2022
      DO 200 J=1,NTRE
      CHANX(J)=CORDX(J)-CORDX(N)
      CHANY(J)=CORDY(J)-CORDY(N)
  200 CONTINUE
      DO 204 J1=1,NOUT
      CHUTX(J1)=OUTX(J1)-CORDX(N)
      CHUTY(J1)=OUTY(J1)-CORDY(N)
  204 CONTINUE
C CALCULATE IDENTITY COMPETETING TREES
      DO 315 K8=1,200
      CAPT(K8)=0
  315 CONTINUE
      DO 316 K9=1,200
      CAPO(K9)=0
  316 CONTINUE
C SET RADIUS OF COMPETITION CATCHMENT
      RAD=(SQRT((607.0/ICOUNT)/2.0))*2.0
      IF(RAD.GT.10.0) RAD=10.0
      K1=0
      K3=0
      K10=0
      K11=0
      K12=0
      K13=0
      K14=0
      K15=0
```

```
124         K16=0
125         K17=0
126         DO 560 J5=1,50
127         CAP1(J5)=0
128         CAP2(J5)=0
129         CAP3(J5)=0
130         CAP4(J5)=0
131         FAR1(J5)=0
132         FAR2(J5)=0
133         FAR3(J5)=0
134         FAR4(J5)=0
135       560 CONTINUE
136         DO 722 J15=1,100
137         COM1(J15)=0
138         COM2(J15)=0
139         COM3(J15)=0
140         COM4(J15)=0
141       722 CONTINUE
142         DO 201 K=1,NTRE
143     C CHECK EACH TREE FOR DIST FROM TARGET TREE
144         IF((CHANX(K)+CHANY(K)).EQ.0) GOTO 201
145         DIST=SQRT((CHANX(K)**2)+(CHANY(K)**2))
146         IF(DIST.GT.RAD)GOTO 201
147     C CHECK IF TREE DEAD
148         IF(BA(K,M).LE.0.001) GOTO 201
149     C ALLOCATE COMPETING TREES TO QUARTILES
150         IF(CHANX(K).LT.0) GOTO 501
151         IF(CHANY(K).LT.0) GOTO 502
152         K10=K10+1
153         CAP1(K10)=K
154         FAR1(K10)=DIST
155         GOTO 201
156       502 K11=K11+1
157         CAP2(K11)=K
158         FAR2(K11)=DIST
159         GOTO 201
160       501 IF(CHANY(K).GT.0) GOTO 503
161         K12=K12+1
162         CAP3(K12)=K
163         FAR3(K12)=DIST
164         GOTO 201
165       503 K13=K13+1
166         CAP4(K13)=K
167         FAR4(K13)=DIST
168       201 CONTINUE
169     C REPEAT FOR TREES OUTSIDE PLOT
170         DO 561 J6=1,50
171         CAPO1(J6)=0
172         CAPO2(J6)=0
173         CAPO3(J6)=0
174         CAPO4(J6)=0
175         LEN1(J6)=0
176         LEN2(J6)=0
177         LEN3(J6)=0
178         LEN4(J6)=0
179       561 CONTINUE
180         DO 202 K2=1,NOUT
181         DSUT=SQRT((CHUTX(K2)**2)+(CHUTY(K2)**2))
182         IF(DSUT.GT.RAD) GOTO 202
183     C ALLOCATE OUT-TREES TO QUARTILES
184         IF(CHUTX(K2).LT.0) GOTO 504
185         IF(CHUTY(K2).LT.0) GOTO 505
```

```
      K14=K14+1
      CAPO1(K14)=K2
      LEN1(K14)=DSUT
      GOTO 202
  505 K15=K15+1
      CAPO2(K15)=K2
      LEN2(K15)=DSUT
      GOTO 202
  504 IF(CHUTY(K2).GT.0) GOTO 506
      K16=K16+1
      CAPO3(K16)=K2
      LEN3(K16)=DSUT
      GOTO 202
  506 K17=K17+1
      CAPO4(K17)=K2
      LEN4(K17)=DSUT
  202 CONTINUE
C COMBINE DISTANCES FROM TARGET TREE
      IF(K10.EQ.0)GOTO 699
      DO 700 J20=1,K10
      COM1(J20)=FAR1(J20)
  700 CONTINUE
  699 IF(K14.EQ.0) GOTO 702
      DO 701 J15=(K10+1),(K10+K14)
      COM1(J15)=LEN1(J15-K10)
  701 CONTINUE
  702 IF(K11.EQ.0) GOTO 704
      DO 703 J7=1,K11
      COM2(J7)=FAR2(J7)
  703 CONTINUE
  704 IF(K15.EQ.0) GOTO 706
      DO 705 J8=(K11+1),(K15+K11)
      COM2(J8)=LEN2(J8-K11)
  705 CONTINUE
  706 IF(K12.EQ.0) GOTO 708
      DO 707 J9=1,K12
      COM3(J9)=FAR3(J9)
  707 CONTINUE
  708 IF(K16.EQ.0) GOTO 710
      DO 709 J10=(K12+1),(K16+K12)
      COM3(J10)=LEN3(J10-K12)
  709 CONTINUE
  710 IF(K13.EQ.0) GOTO 712
      DO 711 J11=1,K13
      COM4(J11)=FAR4(J11)
  711 CONTINUE
  712 IF(K17.EQ.0) GOTO 714
      DO 713 J12=(K13+1),(K17+K13)
      COM4(J12)=LEN4(J12-K13)
  713 CONTINUE
  714 CONTINUE
C TEST FOR CLOSENESS TO TARGET TREE
      TDIS=0
      K19=3
      IF(COM1(1).EQ.0) GOTO 562
      DO 509 K23=1,10
      LIST(K23)=0
  509 CONTINUE
      IF((K10+K14).EQ.1) LIST(1)=1
      IF(LIST(1).GT.0) GOTO 571
      K21=0
      DO 507 K19=1,2
```

```
      FMIN=20
      IF(K19.GT.1) GOTO 725
      DO 530 K18=1,(K10+K14)
      IF(COM1(K18).GT.FMIN) GOTO 530
      FMIN=COM1(K18)
  530 CONTINUE
  725 DO 508 K20=1,(K10+K14)
      IF(COM1(K20).GT.FMIN) GOTO 508
      DO 510 K22=1,10
      IF(K20.EQ.LIST(K22)) GOTO 508
  510 CONTINUE
      FMIN=COM1(K20)
      J16=K20
  508 CONTINUE
      K21=K21+1
      LIST(K21)=J16
  507 CONTINUE
  571 CONTINUE
      DO 531 K1=1,(K19-1)
      IF(LIST(K1).LE.K10) CAPT(K1)=CAP1(LIST(K1))
      IF(LIST(K1).GT.K10) CAPO(K1)=CAPO1((LIST(K1)-K10))
  531 CONTINUE
      DO 800 M5=1,10
      TDIS=(COM1(LIST(M5))**2)+TDIS
  800 CONTINUE
  562 IF(COM2(1).EQ.0) GOTO 563
      DO 511 K24=1,10
      LIST(K24)=0
  511 CONTINUE
      IF((K11+K15).EQ.1)LIST(1)=1
      IF(LIST(1).GT.0) GOTO 572
      K25=0
      DO 513 K27=1,2
      FMIN=20
      IF(K27.GT.1) GOTO 726
      DO 512 K26=1,(K11+K15)
      IF(COM2(K26).GT.FMIN) GOTO 512
      FMIN=COM2(K26)
  512 CONTINUE
  726 DO 514 K28=1,(K11+K15)
      IF(COM2(K28).GT.FMIN) GOTO 514
      DO 515 K29=1,10
      IF(K28.EQ.LIST(K29)) GOTO 514
  515 CONTINUE
      FMIN=COM2(K28)
      J17=K28
  514 CONTINUE
      K25=K25+1
      LIST(K25)=J17
  513 CONTINUE
  572 CONTINUE
      DO 516 K1=K19,((K19-1)*2)
      IF(LIST(K1-2).LE.K11) CAPT(K1)=CAP2(LIST(K1-2))
      IF(LIST(K1-2).GT.K11) CAPO(K1)=CAPO2((LIST(K1-2)-K11))
  516 CONTINUE
      DO 801 M6=1,10
      TDIS=(COM2(LIST(M6))**2)+TDIS
  801 CONTINUE
  563 IF(COM3(1).EQ.0) GOTO 564
      DO 517 K30=1,10
      LIST(K30)=0
  517 CONTINUE
```

```
310         IF((K12+K16).EQ.1)LIST(1)=1
311         IF(LIST(1).GT.0) GOTO 573
312         K31=0
313         DO 519 K33=1,2
314         FMIN=20
315         IF(K33.GT.1) GOTO 727
316         DO 518 K32=1,(K12+K16)
317         IF(COM3(K32).GT.FMIN) GOTO 518
318         FMIN=COM3(K32)
319       518 CONTINUE
320       727 DO 520 K34= 1,(K12+K16)
321         IF (COM3(K34).GT.FMIN) GOTO 520
322         DO 521 K35=1,10
323         IF(K34.EQ.LIST(K35)) GOTO 520
324       521 CONTINUE
325         FMIN=COM3(K34)
326         J18=K34
327       520 CONTINUE
328         K31=K31+1
329         LIST(K31)=J18
330       519 CONTINUE
331       573 CONTINUE
332         DO 522 K1=(1+(K19-1)*2),((K19-1)*3)
333         IF(LIST(K1-4).LE.K12) CAPT(K1)=CAP3(LIST(K1-4))
334         IF(LIST(K1-4).GT.K12) CAPO(K1)=CAPO3((LIST(K1-4)-K12))
335       522 CONTINUE
336         DO 802 M7=1,10
337         TDIS=(COM3(LIST(M7))**2)+TDIS
338       802 CONTINUE
339       564 IF(COM4(1).EQ.0) GOTO 565
340         DO 523 K35=1,10
341         LIST(K35)=0
342       523 CONTINUE
343         IF((K13+K17).EQ.1)LIST(1)=1
344         IF(LIST(1).GT.0) GOTO 574
345         K36=0
346         DO 525 K38=1,2
347         FMIN=20
348         IF(K38.GT.1)GOTO 728
349         DO 524 K37=1,(K13+K17)
350         IF(COM4(K37).GT.FMIN) GOTO 524
351         FMIN=COM4(K37)
352       524 CONTINUE
353       728 DO 526 K39=1,(K13+K17)
354         IF(COM4(K39).GT.FMIN) GOTO 526
355         DO 527 K40=1,10
356         IF(K39.EQ.LIST(K40)) GOTO 526
357       527 CONTINUE
358         FMIN=COM4(K39)
359         J19=K39
360       526 CONTINUE
361         K36=K36+1
362         LIST(K36)=J19
363       525 CONTINUE
364       574 CONTINUE
365         DO 528 K1=(1+(K19-1)*3),((K19-1)*4)
366         IF(LIST(K1-6).LE.K13) CAPT(K1)=CAP4(LIST(K1-6))
367         IF(LIST(K1-6).GT.K13) CAPO(K1)=CAPO4((LIST(K1-6)-K13))
368       528 CONTINUE
369         DO 803 M8=1,10
370         TDIS=(COM4(LIST(M8))**2)+TDIS
371       803 CONTINUE
```

```
372     565 CONTINUE
373   C CALC COMPETING BASAL AREA
374         COMPBA=0
375         DO 206 K4=1,((K19-1)*4)
376         C=CAPT(K4)
377         IF(C.EQ.0) GOTO 206
378         COMPBA=COMPBA+BA(C,M)
379     206 CONTINUE
380         DO 207 K5=1,((K19-1)*4)
381         D=CAPO(K5)
382         IF(D.EQ.0) GOTO 207
383   C CALC PAST DIA FOR TREE OUT OF PLOT
384         AGE=17-(MEASNO-M)
385         X=(DOUT(D)/0.05)-1
386         CB=-1*(0.08759774+((X*0.0434391)+(0.00444384*(X**2))))
387         CC=(1/(18.16906+(-18.76254*(EXP(-0.1311164*X)))))
388         CA=DOUT(D)-(CB*(EXP(-CC*17.0)))
389         Y=(CA+(CB*(EXP(-CC*AGE))))
390         IF(X.LT.1.49) GOTO 804
391         IF(X.GT.8.50) GOTO 804
392         BIAS=(17.5056-(1.23167*AGE))/1000
393         IF(BIAS.LT.0.0) BIAS=0.0
394         Y=Y+BIAS
395     804 R=Y/2
396         BAT=(R**2)*3.1416
397         COMPBA=COMPBA+BAT
398     207 CONTINUE
399   C CALCULATE PRIMARY COMPETITION VARIABLES
400         COMP=COMPBA/BA(N,M)
401         NI=0
402         NO=0
403         DO 721 J13=1,200
404         IF(CAPT(J13).GT.0)NI=NI+1
405         IF(CAPO(J13).GT.0)NO=NO+1
406     721 CONTINUE
407   C CALCULATE AGE AND MEAN DISTANCE TO COMPETITION
408         TCAP=NI+NO
409         IF(TCAP.EQ.0) TCAP=1
410         DIST=SQRT(TDIS/TCAP)
411         AGE=17-(MEASNO-M)
412   C CALCULATE SECONDARY COMPETITION VARIABLES
413         G2=(BA(N,M)**2)
414         AG2=AGE*G2
415         CD=COMP*DIST
416         AD=AGE*DIST
417         IF(M.GT.1) THIN=0
418   C CALCULATE INCREMENT FOR TREE
419         PART1=0.0
420         PART3=0.0
421         ANS=(BA(N,M)*55.31344)-(COMP*0.215962)-(G2*569.7609)
422        1+(AG2*21.3405)+(CD*0.02878043)-(AGE*0.1272772)+(DIST*0.5571002)
423        2-(AD*0.02667115)-(THIN*0.4594533)-6.262149
424         IF(ANS.LT.-16.118096) ANS=-16.118096
425         DIS=EXP(ANS)
426         IF(DIS.GT.0.006) GOTO 935
427         ANS=(BA(N,M)*95.37013)-(COMP*0.1746338)-(G2*1474.932)+
428        3(AG2*54.76479)+(CD*0.02472496)-(AGE*0.2582342)+(DIST*0.2076688)
429        4-(THIN*0.4117763)-5.74979
430         IF(ANS.LT.-16.118096) ANS=-16.118096
431         ANS=EXP(ANS)
432         IF(DIS.GT.0.0015) GOTO 955
433         IF(ANS.GT.0.00015) GOTO 900
```

```
434         ANS= 0.0
435         GOTO 900
436      955 PART1=ANS
437      935 IF(DIS.GT.0.015) GOTO 945
438         ANS=(BA(N,M)*10.54657)-(COMP*0.03748523)-(G2*37.80181)
439        2-(AGE*0.02179714)+(DIST*0.2557503)-(AD*0.008868142)
440        3-(THIN*0.1603143)-5.73553
441         IF(ANS.LT.-16.118096) ANS=-16.119096
442         ANS=EXP(ANS)
443         IF(PART1.LE.0.0) GOTO 965
444         PART2=DIS
445         ANS=(PART1+PART2)/2
446      965 IF(DIS.GT.0.013) GOTO 975
447         GOTO 900
448      975 PART3=ANS
449      945 ANS=(BA(N,M)*1.382439)-(CD*0.006742263)+(DIST*0.1075394)
450        1-(AD*0.003138169)-(THIN*0.09468021)-4.671048
451         IF(ANS.LT.-16.118096) ANS=-16.118096
452         ANS=EXP(ANS)
453         IF(PART3.LE.0.0) GOTO 900
454         PART4=ANS
455         ANS=(PART3+PART4)/2
456    C CALCULATE NEW BASAL AREA
457      900 BA(N,(M+1))=BA(N,M)+ANS
458         IF(ANS.GT.0.0)BA(N,(M+1))=BA(N,(M+1))*1.02
459         IF(ANS.EQ.0.0) GOTO 2024
460    C BOOST LARGEST TREES
461         AGE=AGE+1
462         ACOF=0.919051-(0.0000001288042*(AGE**4.638252))
463         BCOF=AGE/(6.415174-(1.298124*AGE)+(0.07718549*(AGE**2)))
464         CCOF=-1*(AGE/(0.8811129-(0.2046921*AGE)+(0.01236159*(AGE**2))))
465         BOOST=ACOF+(BCOF*BA(N,M+1))+(CCOF*(BA(N,M+1)**2))
466         END1=(AGE*0.007474935)-0.06203361
467         END2=(AGE*0.01532416)-0.06984697
468         IF(BA(N,M+1).GT.END2) BOOST=1.0
469         IF(BA(N,M+1).LT.END1) GOTO 2023
470         IF(BOOST.LT.0.98) BOOST=0.98
471      2023 IF(BOOST.LT.0.95) BOOST=0.95
472         BA(N,M+1)=BA(N,M+1)*BOOST
473         IF(BA(N,M+1).LT.BA(N,M)) BA(N,M+1)=(BA(N,M)+0.00001)
474      2024 IF(M.LE.2) GOTO 2022
475    C CHECK FOR MORTALITY
476    C (IF INC=0 FOR THREE YEARS, TREE IS DEAD)
477         IF(BA(N,(M+1)).EQ.BA(N,(M-2))) BA(N,(M+1))=0
478         IF(BA(N,(M+1)).EQ.0.0) IDEATH=IDEATH+1
479      2022 IF(BA(N,M+1).EQ.0.0) HT(N,M+1)=0.0
480         IF(BA(N,M+1).EQ.0.0)VOL(N,M+1)=0.0
481         IF(BA(N,M+1).EQ.0.0) GOTO 153
482    C PREDICT HEIGHT FROM DIAMETER & AGE
483    C NOTE THERE IS A RANDOM NUMBER ASSOC WITH THE HEIGHT VALUE
484    C  (ADVANCE AGE TO END OF PERIOD)
485         COFA=3.32557+(AGE*1.836691)
486         CRTA=9.849823-(AGE*1.549468)+((AGE**2)*0.06715343)
487         COFA=COFA-(CRTA-1)
488         COFB=-1*(AGE*4.588648-24.55002)
489         COFC=9.72
490         DBH=(SQRT(BA(N,(M+1))/3.1416))*2
491         HT(N,(M+1))=COFA+COFB*EXP(-COFC*DBH)
492    C CONSTRAIN HTS FOR SMALL DBH & OLD TREES
493         IF(DBH.GT.0.188) GOTO 1020
494         IF(AGE.LT.14) GOTO 1020
495         IF(DBH.LT.0.113) HT(N,M+1)=13.87
```

```
      IF(HT(N,M+1).EQ.13.87) GOTO 1020
      IF(AGE.LT.15) GOTO 1020
      IF(DBH.LT.0.138) HT(N,M+1)=17.02
      IF(HT(N,M+1).EQ.17.02) GOTO 1020
      IF(AGE.LT.16) GOTO 1020
      IF(DBH.LT.0.163) HT(N,M+1)=20.19
      IF(HT(N,M+1).EQ.20.19) GOTO 1020
      IF(AGE.LT.19) GOTO 1020
      IF(DBH.LT.0.188) HT(N,M+1)=23.14
 1020 CONTINUE
C FIT RANDOM NUMBER TO HT,(NORMAL DIST ABOUT VALUE)
      DEV=((HT(N,M+1)*1.14)-(HT(N,M+1)))/3
      HT(N,M+1)=G05DDF(HT(N,M+1),DEV)
      VOLU=((DBH**2)*HT(N,M+1)*0.291751)-0.0101147
      IF(VOLU.LT.0.0) VOLU=0.0
      VOL(N,M+1)=VOLU
  153 CONTINUE
      RETURN
       END
      SUBROUTINE PRINT
      CHARACTER LINE,PLOT
      INTEGER ACX,PRY,AGE
      REAL MS,MWA,LAGE,LTAP
      DIMENSION TOTWOL(20),WOL(20),XX(20),PERWOL(20),MWA(400,15)
      DIMENSION ACX(400),PRY(400),PLOT(50,80),LINE(80)
      COMMON DIA(400,15),CORDX(400),CORDY(400)
      COMMON OUTX(300),OUTY(300),N,NTRE,M
      COMMON CHUTX(300),CHUTY(300),MEASNO,CHANX(400),CHANY(400)
      COMMON DOUT(300),NOUT,ICOUNT,BA(400,15)
      COMMON N1,THIN,D2(400,15),IDEATH,HT(400,15),VOL(400,15)
      DO 905 L=1,NTRE
      D2(L,(M+1))=(SQRT(BA(L,(M+1))/3.1416)*2)
  905 CONTINUE
C  PREDICT MEAN WOOD AGE
      AGE=17-(MEASNO-(M+1))
      DO 2000 N1=1,NTRE
      IF(D2(N1,M+1).EQ.0.0) MWA(N1,M+1)=0.0
      IF(D2(N1,M+1).EQ.0.0) GOTO 2000
      TAPER=HT(N1,M+1)/D2(N1,M+1)
      TEMP=AGE*1
      LAGE=ALOG(TEMP)
      LTAP=ALOG(TAPER)
      MWA(N1,M+1)=(TAPER*0.07343226)-(HT(N1,M+1)*0.8309232)
     9+(D2(N1,M+1)*47.9958)-(AGE*TAPER*0.006376464)+
     9(AGE*HT(N1,M+1)*0.05522689)-(AGE*D2(N1,M+1)*2.412636)
     9+(LAGE*3.50306)+(LTAP*3.089157)-17.38164
 2000 CONTINUE
      WRITE(2,2023)
 2023 FORMAT(1H1,//,45X,'RESULTS OF MODEL --- BY TREE',//)
      WRITE(2,911)
  911 FORMAT(1H ,41X,'ACTUAL',10X,'PROJECTED',7X,'PROJECTED',7X,'PROJECT
     5ED',8X,'PROJECTED')
      WRITE(2,910)
  910 FORMAT(1H ,3X,'TREE NUMBER',5X,'INITIAL DIAMETER',3X,
     1'FINAL DIAMETER',3X,'FINAL DIAMETER',6X,'HEIGHT',10X,'VOLUME',7X
     9,'MEAN WOOD AGE',//)
      DO 920 L1=1,NTRE
      WRITE(2,930)L1,DIA(L1,1),DIA(L1,MEASNO),D2(L1,(M+1)),HT(L1,(M+1))
     6,VOL(L1,M+1),MWA(L1,M+1)
  930 FORMAT(1H ,8X,I4,12X,F5.3,13X,F5.3,11X,F5.3,12X,F4.1,13X,F5.3,
     912X,F5.3)
  920 CONTINUE
```

```
C CALCULATE TOTAL VOLUME FOR PLOT
      TOTVOL=0.0
      DO 981 L12=1,NTRE
      TOTVOL=TOTVOL+VOL(L12,M+1)
  981 CONTINUE
C CALCULATE MEAN, STD DEV, HIGHEST AND LOWEST VALUES
      D2TOT=0
      DEVTOT=0
      INUM=0
      ITALLY=0
      DIT=0
      D2T=0
      DIAMAX=DIA(1,MEASNO)
      DIAMIN=DIA(1,MEASNO)
      DO 940 L2=1,NTRE
      IF(DIA(L2,MEASNO).GT.DIAMAX) DIAMAX=DIA(L2,MEASNO)
      IF(DIA(L2,MEASNO).LT.DIAMIN) DIAMIN=DIA(L2,MEASNO)
      DIT=DIT+DIA(L2,MEASNO)
      IF(DIA(L2,MEASNO).GT.0.0)ITALLY=ITALLY+1
  940 CONTINUE
      D2MAX=D2(1,(M+1))
      D2MIN=D2(1,(M+1))
      DO 950 L3=1,NTRE
      IF(D2(L3,(M+1)).GT.D2MAX)D2MAX=D2(L3,(M+1))
      IF(D2(L3,(M+1)).LT.D2MIN)D2MIN=D2(L3,(M+1))
      D2T=D2T+D2(L3,(M+1))
      IF(D2(L3,(M+1)).GT.0.0) INUM=INUM+1
  950 CONTINUE
      AVDIA=DIT/ITALLY
      MORT=NTRE-ITALLY
      AVD2=D2T/INUM
      MORT2=NTRE-INUM
      DO 960 L4=1,NTRE
      IF(DIA(L4,MEASNO).EQ.0.0) GOTO 955
      DEV=(DIA(L4,MEASNO)-AVDIA)**2
      DEVTOT=DEVTOT+DEV
  955 IF(D2(L4,(M+1)).EQ.0.0) GOTO 960
      DEV2=(D2(L4,(M+1))-AVD2)**2
      D2TOT=D2TOT+DEV2
  960 CONTINUE
      SD=SQRT(DEVTOT/(ITALLY-1))
      SD2=SQRT(D2TOT/(INUM-1))
      WRITE(2,980)
  980 FORMAT(1H ,42X,'-----',11X,'-----',28X,'------')
      WRITE(2,970)AVDIA,AVD2,TOTVOL
  970 FORMAT(1H ,35X,'MEAN',3X,F5.3,4X,'MEAN',3X,F5.3,19X,'TOTAL',3X,
     8F7.3)
      WRITE(2,990)SD,SD2
  990 FORMAT(1H ,35X,'SDEV',3X,F5.3,4X,'SDEV',3X,F5.3)
      WRITE(2,935)MORT,MORT2
  935 FORMAT(1H ,35X,'MORT',3X,I4,5X,'MORT',3X,I4)
      WRITE(2,915)DIAMAX,D2MAX
  915 FORMAT(1H ,35X,'DMAX',3X,F5.3,4X,'D2MAX',2X,F5.3)
      WRITE(2,925)DIAMIN,D2MIN
  925 FORMAT(1H ,35X,'DMIN',3X,F5.3,4X,'D2MIN',2X,F5.3)
C CALCULATE MEAN SQUARE OF RESIDUALS
      DIFTOT=0.0
      DO 965 L5=1,NTRE
      DIF=(DIA(L5,MEASNO)-D2(L5,(M+1)))**2
      DIFTOT=DIFTOT+DIF
  965 CONTINUE
      MS=DIFTOT/NTRE
```

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      WRITE(2,975)MS
  975 FORMAT(1H ,52X,'MS-R',2X,F8.6)
C PREDICT DISTRIBUTION OF VOLUME BY WOOD-AGE
      DO 2003 M2=1,20
      TOTWOL(M2)=0.0
 2003 CONTINUE
      DO 2004 N2=1,NTRE
      IF(MWA(N2,M+1).EQ.0.0) GOTO 2004
      DO 2005 M4=1,20
      WOL(M4)=0.0
 2005 CONTINUE
C SET CLASS LIMITS (FOR DISTRIBUTION)
      CI=1.0
      DO 2006 M5=2,AGE
      XX(1)=0.5
      XX(M5)=XX(M5-1)+CI
 2006 CONTINUE
      CI=CI*0.5
C PREDICT PARAMETERS FOR WEIBULL DISTRIBUTION
      A=0.0
      B=(1.224112*MWA(N2,M+1))-0.2910628
      C=4.363046+(AGE*0.3416393)+(MWA(N2,M+1)*1.065332)
     9-(AGE*MWA(N2,M+1)*0.03633757)
     9-((ALOG(AGE*1.0))*2.870408)-((ALOG(MWA(N2,M+1)))*2.314679)
      C=EXP(C)
C PREDICT DISTRIBUTION OF VOLUME BY WOOD-AGE FOR TREE
      TOT=VOL(N2,M+1)
      DO 2008 N3=1,AGE
      WOL(N3)=TOT*(EXP(-((XX(N3)-A-CI)/B)**C)
     9-EXP(-((XX(N3)-A+CI)/B)**C))
 2008 CONTINUE
C TOTAL FOR PLOT
      DO 2009 N4=1,AGE
      TOTWOL(N4)=TOTWOL(N4)+WOL(N4)
 2009 CONTINUE
 2004 CONTINUE
C WRITE RESULTS
      WRITE(2,2010)
 2010 FORMAT(1H1,//,12X,'RESULTS OF MODEL --- FOR PLOT'//)
      WRITE(2,2011)
 2011 FORMAT(1H ,10X,'AGE',10X,'VOLUME',10X'PERCENT',/)
      VOLUME=0.0
      DO 2012 N5=1,AGE
      VOLUME=VOLUME+TOTWOL(N5)
 2012 CONTINUE
C  CORRECT TOTAL FOR DISTRIBUTED VOLUMES
      CORR=TOTVOL/VOLUME
      DO 2020 N9=1,AGE
      TOTWOL(N9)=TOTWOL(N9)*CORR
 2020 CONTINUE
      VOLUME=0.0
      DO 2021 N10=1,AGE
      VOLUME=VOLUME+TOTWOL(N10)
 2021 CONTINUE
      DO 2013 N6=1,AGE
      PERWOL(N6)=TOTWOL(N6)/VOLUME*100
 2013 CONTINUE
      DO 2014 N7=1,AGE
      XY=N7-0.5
      WRITE(2,2015)XY,TOTWOL(N7),PERWOL(N7)
 2015 FORMAT(1H ,9X,F4.1,10X,F6.4,12X,F4.1)
 2014 CONTINUE
```

```
      WRITE(2,2016)
 2016 FORMAT(1H ,23X,'------')
      WRITE(2,2017) VOLUME
 2017 FORMAT(1H ,15X,'TOTAL',3X,F6.3)
      WAGE=0.0
      DO 2018 N8=1,AGE
      WAGE=WAGE+(PERWOL(N8)*N8)
 2018 CONTINUE
      WAGE=(WAGE/100)-0.5
      WRITE(2,2019) WAGE
 2019 FORMAT(1H ,//,20X,'MEAN WOOD-AGE',3X,F5.3)
C THEN PLOT ACTUAL AGAINST PREDICTED VALUES
      DO 985 L6=1,NTRE
      ACX(L6)=IFIX((DIA(L6,MEASNO)*160)+1.5)
      PRY(L6)=IFIX((D2(L6,(M+1))*100)+1.5)
      PRY(L6)=(51-PRY(L6))
  985 CONTINUE
      DO 995 L7=1,80
      LINE(L7)='-'
  995 CONTINUE
      WRITE(2,901)
  901 FORMAT(1H1,///,50X,'PREDICTED DIAMETER AGAINST ACTUAL FINAL',
     7' DIAMETER')
      DO 903 L9=1,50
      DO 904 L10=1,80
      PLOT(L9,L10)=' '
  904 CONTINUE
  903 CONTINUE
      DO 902 L8=1,NTRE
      PLOT(PRY(L8),ACX(L8))='*'
  902 CONTINUE
      WRITE(2,909)
  909 FORMAT(1H ,5X,'PREDICTED DIA (50CM)')
      DO 906 L11=1,50
      WRITE(2,912)(PLOT(L11,L12),L12=1,80)
  912 FORMAT(1H ,25X,'I',80A1)
  906 CONTINUE
      WRITE(2,907)(LINE(L13),L13=1,80)
  907 FORMAT(1H ,26X,80A1)
      WRITE(2,908)
  908 FORMAT(1H ,26X,'0',15X,'10',14X,'20',14X,'30',14X,'40',14X,'50')
      WRITE(2,913)
  913 FORMAT(1H ,50X,'ACTUAL FINAL TREE DIAMETER (CMS)')
      RETURN
      END
C
      SUBROUTINE TEST
C THIS SUBROUTINE CALCS AVERAGE ANN. INCREMENT & DISTIBUTIONS OF
C FINAL DIAMETER & DIAMETER INCREMENT & PRINTS COMPARATIVE DATA
      COMMON DIA(400,15),CORDX(400),CORDY(400)
      COMMON OUTX(300),OUTY(300),N,NTRE,M
      COMMON CHUTX(300),CHUTY(300),MEASNO,CHANX(400),CHANY(400)
      COMMON DOUT(300),NOUT,ICOUNT,BA(400,15)
      COMMON N1,THIN,D2(400,15),IDEATH,HT(400,15),VOL(400,15)
      INTEGER ADC(26),PDC(26),AIC(26),PIC(26),CLASS
      DIMENSION SEC1(400),SEC2(400),SECP(400),TINC(400),PINC(400)
      DIMENSION APER(26),PPER(26),DPER(26),PDP(26)
C CALC AVERAGE ANNUAL INCREMENT VALUES
      DO 1010 L20=1,NTRE
      SEC1(L20)=(((DIA(L20,1)/2)**2)*3.1416)
      SEC2(L20)=(((DIA(L20,(M+1))/2)**2)*3.1416)
      SECP(L20)=(((D2(L20,(M+1))/2)**2)*3.1416)
```

```
744         TINC(L20)=(SEC2(L20)-SEC1(L20))/(MEASNO-1)
745         PINC(L20)=(SECP(L20)-SEC1(L20))/(MEASNO-1)
746    1010 CONTINUE
747    C ALLOCATE TO CLASSES
748         DO 1011 L21=1,26
749         ADC(L21)=0
750         PDC(L21)=0
751         AIC(L21)=0
752         PIC(L21)=0
753         DPER(L21)=0
754         PDP(L21)=0
755         APER(L21)=0
756         PPER(L21)=0
757    1011 CONTINUE
758         DO 1012 L22=1,NTRE
759         CLASS=IFIX((DIA(L22,(M+1))/0.02)+1)
760         ADC(CLASS)=ADC(CLASS)+1
761         CLASS=IFIX((D2(L22,(M+1))/0.02)+1)
762         PDC(CLASS)=PDC(CLASS)+1
763         CLASS=IFIX((TINC(L22)/0.0008)+1)
764         IF(CLASS.LE.0.0) CLASS=1
765         AIC(CLASS)=AIC(CLASS)+1
766         CLASS=IFIX((PINC(L22)/0.0008)+1)
767         IF(CLASS.LE.0) CLASS=1
768         PIC(CLASS)=PIC(CLASS)+1
769    1012 CONTINUE
770    C CALCULATE PERCENTAGES
771         DO 1013 L23=1,26
772         DPER(L23)=(ADC(L23)/FLOAT(NTRE))*100
773         PDP(L23)=(PDC(L23)/FLOAT(NTRE))*100
774         APER(L23)=(AIC(L23)/FLOAT(NTRE))*100
775         PPER(L23)=(PIC(L23)/FLOAT(NTRE))*100
776    1013 CONTINUE
777    C WRITE OUT RESULTS
778         WRITE(2,1014)
779    1014 FORMAT(1H1,/,50X,'COMPARISON OF STAND DIAMETERS AT 17 YEARS')
780         WRITE(2,1015)
781    1015 FORMAT(1H ,/,21X,'DIAMETER CLASS',39X,'INCREMENT CLASS')
782         WRITE(2,1016)
783    1016 FORMAT(1H ,/,12X,'CLASS',12X,'ACTUAL',10X,'PREDICTED',
784        112X'CLASS',12X,'ACTUAL',10X,'PREDICTED')
785         WRITE(2,1017)
786    1017 FORMAT(1H ,/,28X,'NO.',2X,'PERCENT',6X,'NO.',2X,'PERCENT',24X,
787        2'NO.',2X,'PERCENT',6X,'NO.',2X,'PERCENT',/)
788         DO 1018 L24=1,26
789         GAP1=(L24*0.02)-0.02
790         GAP2=(L24*0.0008)-0.0008
791         WRITE(2,1019)GAP1,ADC(L24),DPER(L24),PDC(L24),PDP(L24),GAP2,
792        3AIC(L24),APER(L24),PIC(L24),PPER(L24)
793    1019 FORMAT(1H ,11X,F5.3,9X,I4,4X,F4.1,6X,I4,4X,F4.1,4X,'!',6X,F6.4,7X,
794        4I4,4X,F4.1,6X,I4,4X,F4.1)
795    1018 CONTINUE
796         RETURN
797         END

ID OF LISTING OF FILE :RYDE.TOTALMOD(81,*,1) FOR USER :RYDE AT 1983/06/02__15:42:06

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D OF BATCH :RYDE LOOK AT 1983/06/02__15:42:09
MMMM
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APPENDIX 4

EXAMPLE OF TREE DIAMETER AND LOCATION DATA

The example given is that of a plot 9x9. The plot contains 45 trees and from the 'buffer' zone between plots 96 trees were mapped as possible competitors. The coordinates are in metres with the origin at the plot centre.

Appendix 4

Diameter Data for Plot 9 x 9

1	0175	0188	0208	0231	0249	0268	0285	0297	0310	0323	0342
2	0180	0206	0224	0239	0251	0256	0263	0268	0270	0271	0271
3	0175	0201	0216	0236	0249	0265	0278	0292	0305	0314	0322
4	0157	0163	0175	0180	0185	0188	0188	0188	0190	0191	0191
5	0152	0170	0188	0203	0216	0231	0243	0255	0268	0279	0288
6	0142	0157	0163	0168	0173	0181	0184	0184	0190	0195	0195
7	0165	0180	0201	0216	0231	0245	0257	0265	0270	0279	0271
8	0140	0152	0163	0173	0185	0196	0205	0214	0223	0228	0233
9	0203	0218	0229	0244	0254	0275	0286	0286	0292	0303	0314
10	0224	0257	0287	0312	0328	0341	0353	0357	0374	0388	0392
11	0160	0191	0218	0239	0259	0282	0300	0317	0333	0349	0362
12	0147	0170	0183	0201	0211	0222	0228	0236	0243	0252	0258
13	0155	0173	0191	0206	0216	0229	0240	0252	0263	0274	0287
14	0114	0124	0132	0145	0150	0155	0158	0160	0163	0165	0166
15	0193	0218	0236	0259	0272	0285	0295	0309	0323	0336	0355
16	0203	0229	0244	0262	0272	0290	0298	0305	0316	0323	0333
17	0183	0188	0208	0218	0229	0237	0242	0245	0245	0261	0265
18	0196	0218	0226	0241	0251	0270	0282	0287	0302	0309	0319
19	0213	0216	0239	0257	0272	0280	0293	0299	0331	0343	0352
20	0201	0236	0262	0284	0305	0325	0345	0365	0384	0402	0418
21	0198	0221	0241	0259	0272	0286	0297	0308	0317	0325	0332
22	0165	0191	0213	0236	0259	0278	0283	0285	0290	0289	0291
23	0208	0246	0279	0305	0328	0349	0370	0390	0408	0423	0439
24	0147	0165	0178	0196	0211	0223	0235	0246	0257	0266	0273
25	0185	0201	0216	0229	0239	0249	0251	0254	0264	0262	0269
26	0188	0203	0216	0229	0241	0252	0258	0265	0272	0277	0285
27	0163	0180	0193	0206	0216	0228	0238	0243	0252	0255	0258
28	0173	0188	0196	0193	0198	0210	0214	0218	0219	0221	0222
29	0196	0226	0244	0269	0287	0300	0315	0324	0337	0350	0356
30	0155	0175	0193	0216	0239	0262	0287	0307	0334	0352	0372
31	0206	0216	0234	0254	0274	0285	0296	0300	0308	0315	0318
32	0160	0185	0206	0226	0246	0265	0286	0301	0319	0332	0346
33	0132	0147	0157	0173	0183	0195	0205	0212	0220	0227	0232
34	0208	0236	0262	0287	0310	0331	0348	0365	0382	0397	0415
35	0155	0165	0175	0188	0198	0207	0217	0222	0230	0238	0245
36	0140	0160	0180	0198	0213	0227	0239	0249	0258	0264	0267
37	0216	0246	0262	0284	0300	0316	0336	0350	0366	0376	0385
38	0201	0231	0251	0264	0272	0279	0289	0287	0292	0291	0291
39	0201	0231	0259	0279	0300	0320	0342	0358	0377	0390	0406
40	0150	0160	0170	0178	0185	0189	0192	0192	0200	0197	0203
41	0147	0168	0180	0196	0211	0222	0232	0238	0246	0256	0260
42	0170	0183	0203	0221	0236	0246	0255	0262	0272	0279	0285
43	0196	0213	0226	0241	0254	0273	0281	0288	0297	0306	0313
44	0140	0150	0157	0168	0178	0184	0190	0196	0200	0205	0207
45	0224	0262	0290	0310	0325	0340	0353	0366	0382	0390	0403

45 Trees
Measured 1970-80

END OF LISTING OF FILE :RYDE.VALIDATA(1,*,1).GRD9X9(1) FOR USER :RYDE AT 1983/07/13__1

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END OF BATCH :RYDE LIST AT 1983/07/13__12:23:13

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APP. 4

Location Data for Plot 9x9

1	45		
2	2.50	13.70	
3	7.15	11.20	
4	1.15	11.20	
5	-6.75	11.20	
6	-8.75	11.20	
7	8.00	9.30	
8	5.75	6.90	
9	1.90	6.90	
10	-0.50	6.90	
11	-2.60	6.90	
12	-5.85	6.90	
13	-9.50	6.90	
14	-10.90	5.10	
15	-6.15	5.10	
16	1.75	5.10	
17	4.30	5.10	
18	6.65	5.10	
19	11.70	5.10	X, Y co-ordinates for trees in plot.
20	1.75	2.50	
21	-10.40	2.50	
22	-10.10	0.60	
23	3.40	0.60	
24	14.90	0.60	
25	11.20	-1.60	
26	5.55	-1.60	
27	-7.00	-1.60	
28	-9.35	-1.60	
29	-11.90	-1.60	
30	-8.05	-3.50	
31	-3.10	-3.50	
32	4.40	-3.50	
33	7.46	-3.50	
34	3.10	-6.00	
35	9.05	-7.80	
36	1.40	-7.80	
37	-1.10	-7.80	
38	-3.55	-7.80	
39	-6.60	-7.80	
40	-9.00	-7.80	
41	-9.20	-10.20	
42	3.55	-10.20	
43	8.45	-10.20	
44	4.75	-12.00	
45	0.20	-12.00	
46	-4.25	-12.00	
47	96		
48	-1.15	19.80	179
49	-5.25	19.80	418
50	-11.70	19.80	335
51	-13.60	19.80	306
52	-17.10	19.80	339
53	-6.00	17.90	320
54	-0.30	15.40	300
55	-11.55	15.40	313
56	-16.95	15.40	415
57	-21.35	15.40	418
58	-4.85	13.70	379
59	-7.40	13.70	319
60	-12.05	13.70	303
61	-10.25	9.30	304

X, Y co-ordinates & dbh (ob) mm. for trees in "buffer"

App. 4

62	-16.55	9.30	220
63	-19.30	9.30	398
64	-21.65	9.30	417
65	-16.25	5.10	340
66	-24.40	5.10	364
67	-14.05	2.50	240
68	-16.85	2.50	249
69	-17.30	0.60	138
70	-20.20	0.60	394
71	-24.00	0.60	335
72	-26.20	0.60	315
73	-22.10	-1.60	272
74	-13.60	-3.50	346
75	-16.30	-3.50	259
76	-19.65	-3.50	324
77	-13.70	-7.80	167
78	-16.90	-7.80	387
79	-9.10	-12.00	220
80	-11.55	-12.00	191
81	-16.75	-12.00	332
82	-19.75	-12.00	419
83	-2.20	-16.40	360
84	-9.10	-16.40	235
85	-13.50	-16.40	280
86	-15.90	-16.40	341
87	-17.85	-16.40	213
88	-7.15	-19.00	282
89	-9.70	-19.00	196
90	-12.40	-19.00	323
91	1.50	19.80	322
92	3.80	19.80	314
93	5.50	19.80	220
94	9.90	19.80	372
95	19.30	19.80	428
96	15.25	17.90	258
97	4.70	15.40	320
98	9.90	15.40	391
99	16.00	15.40	337
100	19.25	15.40	290
101	12.30	13.70	239
102	19.00	13.70	365
103	21.65	13.70	181
104	23.85	13.70	214
105	9.80	11.20	230
106	21.80	11.20	75
107	23.95	11.20	319
108	11.30	9.30	270
109	15.40	9.30	341
110	19.30	9.30	173
111	15.15	6.90	330
112	21.45	6.90	179
113	18.70	5.10	340
114	21.85	5.10	368
115	25.85	5.10	295
116	20.25	2.50	282
117	25.85	2.50	236
118	20.35	0.60	228
119	23.35	0.60	238
120	22.85	-1.60	193
121	12.95	-3.50	377
122	16.30	-3.50	327
123	19.40	-3.50	258

App. 4

```
124    24.55 -3.50 226
125    12.85 -6.00 302
126    15.30 -7.80 334
127    17.95 -7.80 296
128    20.95 -7.80 197
129    23.75 -7.80 357
130    17.00-10.20 329
131    21.75-10.20 303
132    12.80-12.00 259
133    18.30-12.00 198
134     1.70-14.70 291
135     6.50-14.70 243
136     9.60-14.70 344
137    29.00 14.70 191
138     0.20-16.40 250
139     2.35-16.40 312
140     8.15-16.40 322
141    13.25-16.40 363
142     3.25-19.00 249
143     8.70-19.00 353

END OF LISTING OF FILE :RYDE.VALDATA(1,*,1).LOC9X9(1) FOR USER
**********************************************************************

END OF BATCH :RYDE LIST AT 1983/07/13__12:22:48
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APPENDIX 5

COPY OF PROGRAM WOODAGETREE

This is a copy of the program used to calculate the mean wood age and percentage distribution of volume by mean wood age for trees which have been assessed by stem analysis. For each tree, results are given for each year from age at felling to six years.

```
      PROGRAM WOODAGETREE
C     PHYSIOLOGICAL AGE PROGRAMME
      REAL MEARAD
      COMMON DIFFHT,VOLS,VOLDIF,RADII,HITES,MEARAD,PERCEN,AGEVOL,N,M
      COMMON ITEST
      DIMENSION HITES(15),RADII(4,20,15),MEARAD(20,15),DIFFHT(15)
     DIMENSION V(20,25),VOLS(20,25),VOLDIF(20,25),AGEVOL(20),PERCEN(20)
      INTEGER B,C,D,PLOT,TREE,      E
      READ(1,90)PLOT,NUM
   90 FORMAT (2I3)
  100 READ(1,1)TREE,N,M
    1  FORMAT (3I3)
C  ENTER RADII
      READ(1,2)(HITES(I1),I1=1,M)
    2 FORMAT (13F6.2)
      B=N+1
      DO 53 I4 =1,M
      B=B-1
        DO  52 I2=1,4
       READ(1,4)(RADII(I2,I3,I4),I3=1,B)
    4   FORMAT(20F4.3)
   52 CONTINUE
   53  CONTINUE
      CALL CHECK
      IF(ITEST.GT.0)GOTO 68
C  CALCULATE MEANS
      D=N
      DO 61 I6=1,M
      DO 62 I5=1,D
      MEARAD(I5,I6)=(RADII(1,I5,I6)+RADII(2,I5,I6)+RADII(3,I5,I6)
     1  +RADII(4,I5,I6))/4
   62 CONTINUE
      D=D-1
   61 CONTINUE
C  CALCULATE HEIGHT DIFFERENCES
      DO 6 I7=1,(M-1)
    6 DIFFHT(I7)=HITES(I7+1)-HITES(I7)
      CONTINUE
C CALCULATE CONE VOLUME
      DO 7 I8=1,(M-1)
    7 VOLS(1,I8)=(.333*DIFFHT(I8)*(MEARAD(1,I8)**2)*3.1416)
      CONTINUE
C CALCULATE LOG VOLUMES
      E=N
      DO 31 J=1,(M-1)
      DO 8 I=2,E
      VOLS(I,J)=(((MEARAD(I,J)**2)+(MEARAD(I-1,J+1)**2))/2)*3.1416
     2  *DIFFHT(J)
    8 CONTINUE
      E=E-1
   31 CONTINUE
C CALCULATE SHEATH VOLUMES
      C=N
      DO 32 I9=1,(M-1)
      DO 9 L=2,C
      VOLDIF (L,I9)=VOLS(L,I9)-VOLS(L-1,I9)
    9 CONTINUE
      C=C-1
      VOLDIF(1,I9)=VOLS(1,I9)
   32 CONTINUE
      WRITE(2,40)
```

```
 40   FORMAT(1H ,12X,'VOLUME BY WOOD-AGE ')
      WRITE(2,41)PLOT
 41   FORMAT(1H ,3X,'PLOT NO. ',I3)
      WRITE(2,42)TREE
 42   FORMAT(1H ,3X,'TREE NO. ',I3)
 50   CALL PRINTO
      N=N-1
      M=M-1
      IF (N.GT.0) GOTO 50
 68    NUM=NUM-1
      IF (NUM.GT.0) GOTO 100
       STOP
      END
      SUBROUTINE PRINTO
      INTEGER X
       REAL MEARAD
      COMMON DIFFHT,VOLS,VOLDIF,RADII,HITES,MEARAD,PERCEN,AGEVOL,N,M
      DIMENSION HITES(15),RADII(4,20,15),MEARAD(20,15),DIFFHT(15)
     DIMENSION V(20,25),VOLS(20,25),VOLDIF(20,25),AGEVOL(20),PERCEN(20)
      DIMENSION WTVOL(20)
C CALCULATE VOLUMES BY PHYSIOLOGICAL AGE
      S=1
      DO 17 I20=1,20
 17   AGEVOL(I20)=0
      CONTINUE
      X=M
 20   DO 10 I10=1,(X-1)
 10   AGEVOL(S)=VOLDIF(S,I10)+AGEVOL(S)
      CONTINUE
      S=S+1

      IF (S.LE.(N+2-X)) GOTO 20
      X=X-1
      IF(S.LE.N) GOTO 20

      TOTAL=0
      DO 11 I11=1,N
 11   TOTAL=TOTAL+AGEVOL(I11)
      CONTINUE
      DO 12 I12=1,N
 12   PERCEN(I12)=(AGEVOL(I12)/TOTAL)*100
      CONTINUE
      WRITE (2,13)N
 13   FORMAT ( 1H ,3X,'TREE AT AGE ',I3)
      WRITE(2,21)
 21   FORMAT (1H ,8X,'WOOD AGE',2X,'VOLUME (M3)',3X,'PERCENT'//)
      DO 14 I13=1,N
      AGE=(I13)-0.5
      WRITE (2,15)AGE,AGEVOL(I13),PERCEN(I13)
 15   FORMAT(1H ,8X,F4.1,6X,F8.6,5X,F8.4)
 14   CONTINUE
      WRITE(2,82)
 82    FORMAT(1H ,18X,'--------'//)
      WRITE (2,16)TOTAL
 16   FORMAT (1H ,11X,'TOTAL= ',F8.6//)
      DO 80 I14=1,N
        WTVOL(I14)=I14*PERCEN(I14)
 80     CONTINUE
        WTTOT=0
        DO 81 I15=1,N
        WTTOT=WTTOT+WTVOL(I15)
 81     CONTINUE
```

```
124           AVAGE=(WTTOT/100)-0.5
125           WRITE(2,43)AVAGE
126      43   FORMAT(1H ,10X,'MEAN WOOD AGE= ',F6.3//)
127           RETURN
128           END
129           SUBROUTINE CHECK
130   C CHECKS TO SEE THAT RADII INCREASE IN VALUE, DETECTS ONE ERROR PER LINE
131           REAL MEARAD
132           COMMON DIFFHT,VOLS,VOLDIF,RADII,HITES,MEARAD,PERCEN,AGEVOL,N,M
133           COMMON ITEST
134           DIMENSION HITES(15),RADII(4,20,15),MEARAD(20,15),DIFFHT(15)
135           DIMENSION V(20,25),VOLS(20,25),VOLDIF(20,25),AGEVOL(20)
136           DIMENSION PERCEN(20)
137           INTEGER X
138           ITEST=0
139           X=N
140           DO 71 I=1,M
141           DO 72 J=1,4
142           DO 73 K=2,X
143           IF (RADII(J,K,I).LT.RADII(J,(K-1),I)) GOTO 74
144      73   CONTINUE
145      72   CONTINUE
146           X=X-1
147      71   CONTINUE
148           GOTO 76
149      74   WRITE(2,75)J,K,I,RADII(J,K,I)
150      75   FORMAT(1H ,'DATA ERROR IN RADII AT CO-ORDS = ',3I5,F6.2)
151           ITEST=1
152           IF (I.LT.M) GOTO 73
153          IF(J.LT.4) GOTO 73
154      76   RETURN
155           END

END OF LISTING OF FILE :RYDE.WOODAGETREE(26,#,1) FOR USER :RYDE AT 1983/07/13__12:20:23

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END OF BATCH :RYDE LIST AT 1983/07/13__12:20:26
RRRR
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