ACTA FORESTALIA FENNICA

Euan G. Mason and A. Graham D. Whyte

Modelling Initial Survival and Growth of Radiata Pine in New Zealand

255 · 1997

ACTA FORESTALIA FENNICA

Publishers The Finnish Society of Forest Science
The Finnish Forest Research Institute

Editors Editor-in-chief Eeva Korpilahti
Production editors Tommi Salonen, Seppo Oja

Editorial Office Unioninkatu 40 A, FIN-00170 Helsinki, Finland
Phone +358 9 857 051, Fax +358 9 625 308, E-mail silva.fennica@metla.fi,
WWW http://www.metla.fi/publish/acta/

Managing Board Erkki Annila (The Finnish Forest Research Institute), Jyrki Kangas (The Finnish Forest Research Institute), Esko Mikkonen (University of Helsinki), Lauri Valsta (The Finnish Forest Research Institute), Harri Vasander (University of Helsinki), and Seppo Vehkamäki (University of Helsinki)

Editorial Board Per Angelstam (Grimsö Wildlife Research Station, Sweden)
Julius Boutelje (Swedish University of Agricultural Sciences, Sweden)
Finn H. Brække (Swedish University of Agricultural Sciences, Sweden)
J. Douglas Brodie (Oregon State University, USA)
Raymond L. Czaplewski (USDA Forest Service, USA)
George Gertner (University of Illinois, USA)
Martin Hubbes (University of Toronto, Canada)
William F. Hyde (Virginia Polytechnic Institute and State University, USA)
Jochen Kleinschmit (Lower Saxony Forest Research Institute, Germany)
Michael Köhl (Swiss Federal Institute for Forest, Snow and Landscape Research, Switzerland)
Noel Lust (University of Gent, Belgium)
Bo Långström (Swedish University of Agricultural Sciences, Sweden)
William J. Mattson (USDA Forest Service, USA)
Robert Mendelsohn (Yale University, USA)
Hugh G. Miller (University of Aberdeen, United Kingdom)
John Pastor (University of Minnesota, USA)
John Sessions (Oregon State University, USA)
Jadwiga Sienkiewicz (Environment Protection Institute, Poland)
Richard Stephan (Federal Research Centre for Forestry and Forest Products, Germany)
Elon S. Verry (USDA Forest Service, USA)
A. Graham D. Whyte (University of Canterbury, New Zealand)
Claire G. Williams (Texas A&M University, USA)

Aim and Scope Acta Forestalia Fennica publishes monographs in forest science. These may be original research articles or comprehensive reviews aiming at a synthesis of knowledge in a particular topic. The series covers all aspects of forest science, both basic and applied subjects. Manuscripts are subject to peer review.

ACTA FORESTALIA FENNICA

255 · 1997

Euan G. Mason and A. Graham D. Whyte

Modelling Initial Survival and Growth of Radiata Pine in New Zealand

The Finnish Society of Forest Science — The Finnish Forest Research Institute

Mason, E.G. & Whyte, A.G.D. 1997. Modelling initial survival and growth of radiata pine in New Zealand. Acta Forestalia Fennica 255. 38 p.

A sensitive framework has been developed for modelling young radiata pine survival, its growth and its size class distribution, from time of planting to age 5 or 6 years. The data and analysis refer to the Central North Island region of New Zealand. The survival function is derived from a Weibull probability density function, to reflect diminishing mortality with the passage of time in young stands. An anamorphic family of trends was used, as very little between-tree competition can be expected in young stands. An exponential height function was found to fit best the lower portion of its sigmoid form. The most appropriate basal area/ha exponential function included an allometric adjustment which resulted in compatible mean height and basal area/ha models. Each of these equations successfully represented the effects of several establishment practices by making coefficients linear functions of site factors, management activities and their interactions. Height and diameter distribution modelling techniques that ensured compatibility with stand values were employed to represent the effects of management practices on crop variation. Model parameters for this research were estimated using data from site preparation experiments in the region and were tested with some independent data sets.

Keywords: growth modelling, young crops, radiata pine, New Zealand
Authors' address: University of Canterbury, School of Forestry, Private Bag 4800, Christchurch, New Zealand. Fax +64 3 364 2124. E-mail e.mason@fore.canterbury.ac.nz
Accepted: 27 February 1997

ISBN 951-40-1559-2
ISSN 0001-5636
Tampere 1997, Tammer-Paino Oy

Contents

Symbols

d	Differential
dbhob	Diameter at breast height outside bark, centimetres
e	2.71828182846
G	Basal area, square metres per hectare
h	Height, metres
ha	Hectare
k	Allometric capacity of stand to grow when $G = 0$, square metres per hectare
log	Natural logarithm of the expression which follows in parentheses
m	Metres
M	Mortality, percentage
N	Number of stems, integer/hectare
RCD	Root collar diameter, centimetres
RGM	Relative growth modifier
S	Survival, percentage
T	Time, years
V	Independent variable
f	Function of
α	Parameter, real number
β	Parameter, real number
δ	Parameter, real number
%	Percentage

1 Introduction

The period of establishment of forest plantations is a time of opportunity for forest managers to influence the long-term productivity and quality of crops, provided that they have access to the right information. Studies described here are aimed at developing appropriate structures for documenting the information required, thus ensuring that decisions about what site preparation, what planting density, what releasing and what fertilising to do in the early years of a radiata pine crop's life are cost-effective. Evaluating the cost-effectiveness of any single silvicultural operation requires long-term forecasts of production.

The annual cost of site preparation and planting in New Zealand's plantations was estimated to be NZ$19.5 million in 1987, based on returns from a nationwide questionnaire. It was expected that 33 000 hectares of plantation would be either replanted or newly planted (Trewin and Mason 1991), representing a cost of NZ$590/ha (NZ$1.00 = US$0.67 as of July 1995), an amount which reflects the widely held perception that establishment treatments strongly influence crop profitability. Since then, the areas planted and the costs per hectare have both risen. About 108 000 ha of plantation were newly planted or replanted in 1994, and this level of establishment is likely to persist or even expand in the next few years. Quantitative and qualitative representations of the establishment system would help managers make decisions about how best to establish stands in any given set of circumstances.

Managers have a range of alternative actions which they can incorporate in a plantation establishment strategy. Two factors are crucial for good establishment:

(i) the state of the seedling immediately after planting;
(ii) the state of the site in which the seedling grows.

Components of these two factors and their interrelationships are shown in Fig. 1 (see p. 9).

The state of radiata pine (*Pinus radiata* D. Don) seedlings can be modified by genotype selection (Shelbourne 1986), nursery practice (Menzies 1986, 1988), handling practice during transplanting (Trewin and Cullen 1985, Trewin and Hunter 1986), and planting (Mason 1985). The state of a site can be improved by land clearing (Mason and Cullen 1986), cultivation (Mason and Cullen 1986), fertilisation (Hunter and Skinner 1986), and weed control (Preest 1985) operations. The state of a site can be inadvertently lowered in quality by land clearing (Ballard 1978) and by harvesting operations (Murphy 1983). This paper focusses on cultivation, spacing, weed control and fertilisation factors.

In controlled experiments that test alternative establishment strategies throughout New Zealand, variables have been measured during the first five years, all of which could directly affect plantation profitability. Reductions in mortality after transplanting seedlings, reductions in stem defect, and increases in crop uniformity all contribute to lower numbers of seedlings required per unit area, and hence cost of establishment, to achieve a desired crop quality. More rapid initial height growth means that trees spend less time with their crowns close to the ground, where temperature extremes and weed competition can reduce survival and growth.

Long-term benefits from gains generated during establishment include reduced stem defect and more rapid growth. The value of long-term benefits to crops of radiata pine in New Zealand has been formally estimated by only a few researchers (eg: Preest 1977, Woollons *et al.* 1983, Balneaves and McCord 1990). Overseas literature on this topic is also scarce; Wilhite and Jones (1981) and Snowdon and Waring (1984) represent two of the few found. Evaluating the most cost-effective establishment strategy requires a consideration of both short- and long-term effects, both of which trends are likely to vary from site to site.

An establishment decision-support system to assist forest managers in this regard should, therefore, comprise both mathematical models and knowledge-based representations so that all relevant factors are considered in an integrated fashion over the short- and long-terms.

Early growth of tree crops up to age 3 years has not previously been modelled in New Zealand to take into account optimal establishment activities. Existing growth and yield modelling techniques (eg: Garcia 1988) assumed average treatments and needed modification, therefore, in order to accommodate factors relevant to plantation establishment. Current growth and yield models for radiata pine in New Zealand are sensitive to changes in stand density and site occupancy such as pruning and thinning (Garcia 1990), but rarely allow for changes in site quality other than through use of so-called site index, nor do they allow for alterations in seedling quality, site preparation, and weed competition.

Reliable models which can reflect the effects that differences in the condition of seedlings and/or artificial changes in site may induce in later crop performance are likely to result from careful, process-oriented research. To date, this research remains incomplete. There exists, however, a large database of field trials to examine the effects of various site preparation strategies on the survival, growth, and in some cases stem form of radiata pine in New Zealand (Mason 1991). A summary of this information in the form of models of initial radiata pine survival and growth, with inferences about the likelihood and magnitude of site preparation effects for particular sites, would be a valuable decision tool for managers to access and utilise.

1.1 Study Objective

The main objective of the work reported here was to develop models of the initial survival and growth of radiata pine in the Central North Island region of New Zealand which adequately reflected a wide range of site qualities and treatments. Initially, the existing database of site preparation experiments and early growth plots used (Mason 1991, 1992), allowed models of the likelihood of radiata pine mortality during the first five years of a rotation to be developed. Using the same data set, size class distribution models for radiata pine tree heights and diameters at breast height applicable to the first five years of a rotation were also developed.

Constructing such a model for the Central North Island region necessitated the development of a modelling framework for very young stands which could eventually be used to represent initial stand development in other regions, preferably through the addition of additional independent variables rather than as stand-alone regional versions of the model. These extensions are the subject of ongoing future research. The aim of the studies described here was to generate and test the required framework in a locality where plantation forestry is concentrated.

Acknowledgements. The authors wish to thank the New Zealand Forest Research Institute for allowing access to data obtained from the Central North Island region. Thanks also to the many people who were involved at various stages with establishment and remeasurement of the experiments.

2 A Theoretical Framework for Modelling Initial Growth

Growth prior to crown closure has the following unique features which may require representations somewhat different from those commonly employed in growth and yield models for older crops:

(i) there may be little competition between trees prior to canopy closure at the initial spacings (typically between 4 × 2 and 5 × 3 m) which are commonly employed in New Zealand's radiata pine plantations;
(ii) tree size at time of planting is independent of site quality;
(iii) there are often large effects of microsites on growth;
(iv) the properties of microsites can easily be changed through site preparation, and these changes often affect tree survival and growth;
(v) treatments applied to trees prior to planting can have a significant effect on initial survival and growth;
(vi) early growth of crops is concerned with processes before current annual increment curves peak, whereas later growth models are more usually associated with periods after those peaks.
(vii) young trees less than breast height (1.40 m above ground in New Zealand or 1.30 m in height in many other countries) have not attained a diameter at breast height.

The first of the above suppositions was based, however, on conjecture, and needed further investigation. An analysis of early data from Nelder design spacing experiments (Mason 1992) showed that:

(i) anamorphic[1] mortality functions were more likely to fit the data than polymorphic ones, as no between-tree competition was detected prior to age five;
(ii) exponential functions were likely to provide a good representation of initial height and basal area growth, as trees' capacities to grow would be limited by their existing sizes, and be unaffected by between-tree competition;
(iii) height growth appeared to increase with stocking/ha in several of the years before any effect of stocking on diameter was detected.

These observed patterns confirmed that a considerable theoretical research effort was required to ascertain what functional forms were likely to be useful for modelling initial growth.

2.1 Mortality

In the absence of specific information about each tree, mortality of trees not competing with one another might be considered to reflect a random process over time, and should therefore follow a Poisson probability density function, derived from:

$$\frac{dN\,/\,dT}{N} = K \qquad (1)$$

where N and T are symbols for stems per unit area and crop age in years respectively and K varies with crop and conditions.

However, freshly planted seedlings may be less likely to die with the passage of time as a consequence of two influences:

(i) the act of transplanting seedlings from nurseries to field sites can cause stress which results in mortality shortly after planting, a result that lessens with the passage of time;
(ii) the range of temperatures encountered and the

---

[1] The terms "anamorphic" and "polymorphic" refer to families of monotonic curves of the same functional form that have not or have common asymptotes respectively (see Vanclay, 1994 p. 279, 282).

> likely competition from weeds are more severe when the tops of trees are close to ground level, while the effects of these factors on mortality may well lessen as trees increase in size.

The numerical value of K would therefore change with time as well as species and location:

$$\frac{dN/dT}{N} = \alpha T^{\beta} \qquad K = \alpha T^{\beta} \tag{2}$$

When solved, the derivative expression results in a form of the well-known Weibull probability density function. The functional form should be anamorphic, as the percentage of deaths would be independent of stocking.

Other modellers have used similar approaches. The survival function used in the Lake States by Belli (1987), for example, was one of exponential decay, of the form:

$$S_T = 100e^{-\alpha T^{\beta}} \tag{3}$$

where S_T = survival percentage at the end of stand age T. Converting this function to a representation of mortality (M_T):

$$M_T = 100(1 - e^{-\alpha T^{\beta}}) \tag{4}$$

and taking the derivative, gives a Weibull probability density function:

$$M'_T = 100\alpha\beta T^{\beta-1}e^{-\alpha T^{\beta}} \tag{5}$$

In all but one species and site cases, Belli found β to be less than one, indicating a decline in mortality with time.

It might be expected that α and β should vary, however, with seedling quality and site quality. Belli (1987) identified different regression coefficients for different site preparation techniques, but multiplied each function by a factor depending on delays in planting or length of storage. The rationale for this difference in representation between seedling quality and site quality was not made clear. It required further study as has been carried out and presented here.

The survival function employed by Payandeh (1987) was also similar to Belli's approach, but lacked a parameter denoting the power of time, thus resulting in a less malleable function. He used dummy variables to denote the effects of site preparation, weed control, stock type, transplanting delay, container size and planting season, all of which were linearly related to the α parameter. That was a useful way of attacking problems like this for a preliminary investigation, but it needed to be refined.

The function of most use for the purposes of initial growth modelling was expected to be a variation of Belli's (1987) function, with the coefficients related to site and seedling quality.

2.2 Height

Prior to canopy closure, one might expect that growth should be exponential, with larger trees having greater leaf and root surface areas than smaller trees. A malleable exponential growth function for arithmetical mean height would be:

$$\frac{d\bar{h}}{dT} = \gamma \bar{h}^{\delta} \tag{6}$$

Solving (6) leads to:

$$\bar{h}_T = \bar{h}_0 + \alpha T^{\beta} \tag{7}$$

where:

$$\alpha = ((1-\delta)\gamma)^{\frac{1}{1-\delta}} \qquad \beta = \frac{1}{1-\delta} \tag{8}$$

Equation (7) has been used for modelling mean heights of young conifer crops in the Lake states (Belli 1987, Belli and Ek 1988). Separate models were estimated for different species and site preparation treatments in those studies.

It is feasible to express the coefficients of Equation (7) as linear functions of site preparation dummy variables and their interactions, thus fitting one model to data from a range of treatments. Variables representing site quality prior to treatment might be similarly included. This would lead to a conceptual model different from that shown in Fig. 1, with stand state prior to first thinning made an output function of pre-treatment site quality, site preparation, and their interactions (Fig. 2). Using the state of the site prior to modification in this way avoids the need to measure the actual changes in it brought about by site preparation.

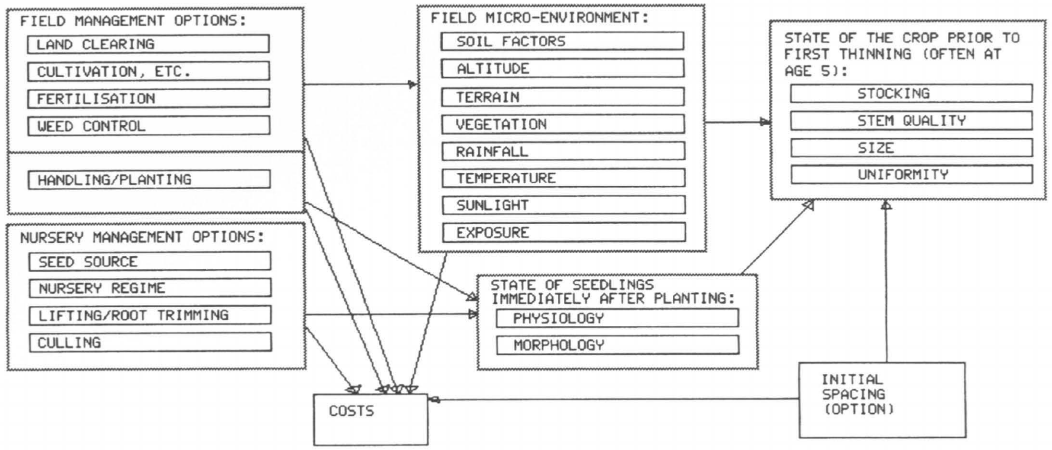


Fig. 1. A conceptual model of plantation establishment.

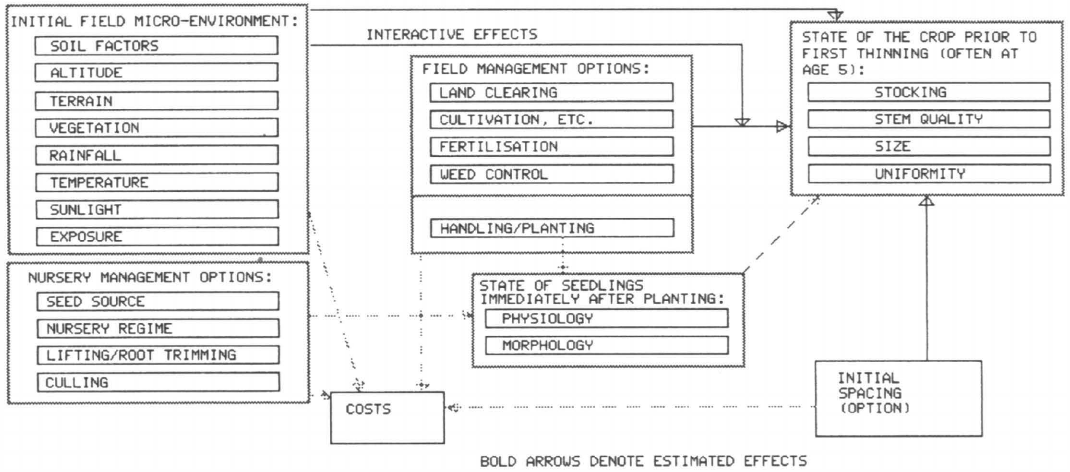


Fig. 2. A revised conceptual model of establishment compatible with the information in the available database.

2.3 Basal Area

Dbhob and basal area are undefined for trees with heights less than 1.40 m, and this leads to some interesting theoretical considerations. Basal area per hectare was not modelled by the other initial growth modellers mentioned above (Payandeh 1987, Belli 1987, Belli and Ek 1988), perhaps because the crops they were dealing with took much longer to reach breast height. Radiata pine in New Zealand, however, generally reaches that height in less than three years. Stand basal area has been considered a useful measure of density in many growth and yield models. It is an input state variable for most radiata pine growth and yield models in New Zealand and so it is vital to be able to predict it from early silviculture.

Basal area growth can be considered as a function of basal area plus a "relative growth modifier (RGM)" which transforms the function from an exponential to a sigmoid:

$$\frac{dG}{dT} = f(G, RGM) \tag{9}$$

Such functions exploit the allometric relations between basal area and growth surfaces of stands (such as leaf surface area), and imply that if $G = 0$, then:

$$\frac{dG}{dT} = 0 \qquad (10)$$

This condition is clearly not met in real tree crops, because trees less than 1.40 m in height in the stand still have considerable leaf and root surface areas, and grow quite rapidly through the point where height = 1.40 m. One would therefore expect that basal area growth would be underestimated by equations with forms similar to Equation 9 at times when basal area is close to 0.

A possible solution to this difficulty is to represent basal area growth as a function of basal area plus k:

$$\frac{dG}{dT} = f((G+k), RGM) \qquad (11)$$

where k represents the allometric capacity of the stand to grow when $G = 0$. A modified Gompertz basal area function used by Whyte and Woollons (1990) would make Equation 11 become:

$$\frac{dG}{dT} = (G+k)(-\beta \ln(\gamma)\gamma^{T}) \qquad (12)$$

When solved the generalised yield function is:

$$G = e^{\alpha-\beta\gamma^{T}} - k \qquad (13)$$

which represents a translation of the origin down the Y axis, and gives rise to the question of defining k. Intuitively, k could well be some function of stocking and site quality. Garcia (1984) confronted a similar problem when defining closure of young stands, and represented it as a function of basal area and stems per hectare.

During the initial growth phase, when the *RGM* has little influence on the shape of the function, basal area functions are approximately exponential, and k can be usefully defined as follows:

$$G_T = \alpha N_0 T^{\beta} - k \qquad (14)$$

where N_0 = initial stocking, introduced because the trees are not competing with one another and G_T (basal area at any stand age T) should be proportional to stocking. If $G_T = 0$:

$$k = \alpha N_0 T^{\beta}_{G=0} \qquad (15)$$

where $T_{G=0}$ is the crop age when $G_T = 0$. Therefore, for T values where the trees are greater than 1.40 m in height:

$$G_T = \alpha N_0 T^{\beta} - \alpha N_0 T^{\beta}_{G=0} \qquad (16)$$

$T_{G=0}$ can be obtained from the height function, resulting in compatible height and basal area functions, where $G_T = 0$ when mean height = 1.40 m. Such an approach results in a certain lack of independence, as with any repeated measures problem, but it need not deter the fitting of functions, as long as statistical bias is acknowledged and allowed for. It might be possible to circumvent this problem by simultaneously estimating the parameters of the height and basal area functions, except that height measurements lower than 1.40 m have no associated *dbhob* measurements.

It was anticipated that the coefficients for Equation 16 might be linearly related to measures of site quality, dummy variables denoting site preparation treatments and their interactions. This also represented a change from the conceptual structure shown in Fig. 1 to that shown in Fig. 2, where the state of the stand at age 5 is a function of site characteristics prior to modification, site modification strategy, and state of seedlings after planting. This change in structure was necessary because variables describing the site state before and after manipulation had not been measured in the experiments for which growth and mortality data were available.

Parameters for the initial growth model were all estimated with functions in yield form, for two reasons:

(i) *dbhob* was measured only once in many of the site preparation experiments which were available;
(ii) when deciding on site preparation treatments, managers would be unlikely to know tree dimensions other than at time of planting, and a projection from other ages was thus unnecessary.

Models in projection form may eventually be useful for representing the development of young crops with varying levels of weed competition from year to year, but there were inadequate data

available to build such models for the studies described here.

Modelling diameter and possibly height distributions of trees during the establishment phase allows an interface between models of initial growth and of diameter distributions at later ages, and also enables managers to gain a visual representation of predicted crop variation. In addition, the distribution of tree sizes is highly relevant to the process of evaluating the financial worth of a stand, because of the importance of tree size in logging, handling, transporting and utilising operations. Without adequate characterisation of size-class distributions, too much sensitivity is lost when detailed financial comparisons are to be made.

Given the need for simple, practical models, and the usefulness of tree size-class information, a size-class distribution model of radiata pine during the establishment phase was considered the ideal form.

3 Methods

3.1 Data Available

3.1.1 Experiments on Establishment Treatments

A catalogue was compiled of site preparation and other experiments throughout New Zealand dealing with radiata pine establishment, which contained treatments that might be used to build growth models. Criteria for selection were:

(i) the species grown was *Pinus radiata* D.Don;
(ii) measurements of height, *dbhob* and/or root collar diameter were available between ages 0 and 5;
(iii) the stock planted had been grown from seed of a minimum genetic quality (either climbing select or seed orchard with growth and form improvement ratings ranging from 6 to 13 (Vincent and Dunstan 1989));
(iv) the seedlings had been raised through a bare-root nursery system, with a certain minimum standard of handling and planting quality.

In some cases, data were available on the same site from either several establishment techniques, or two levels of nursery, handling and planting quality. It was considered that an analysis of the effects of other establishment techniques or of poor nursery, handling and planting practices on a range of sites would require more data than were immediately available.

From the 131 experiments meeting these criteria nationwide (see Mason 1991), a sub-population of 27 experiments was chosen for the detailed study described here.

Height, diameter and survival data were summarised by location, ripping, mounding, phosphate fertilisation (15 g/tree after planting, or the closest equivalent), nitrogen fertilisation (15 g/tree after planting or the closest equivalent), re-fertilisation (or slow release applications at time of planting), weed control (estimated number of weed-free years), initial stocking, and crop age at time of measurement. This compilation produced records of growth and associated information for the 27 experiments. Each record contained (in the order in which they appear in the database):

(i) an experiment identifier, consisting of an alphabetic conservancy code and a number;
(ii) years since planting until each set of measurements was conducted;
(iii) dummy variable (1=yes, 0=no) to denote ripping;
(iv) dummy variable to denote mounding or not;
(v) estimated number of years of weed control;
(vi) number of grams per tree of elemental phosphate applied after planting;
(vii) number of grams per tree of elemental nitrogen applied after planting;
(viii) dummy variable denoting whether the diameter measurements were at breast height (1) or at root collar diameter (0);
(ix) number of tree height measurements;
(x) mean height of all living trees at time of measurement;
(xi) mean diameter (at breast height or root collar) of all trees;
(xii) minimum height;
(xiii) minimum diameter (at breast height or root collar);
(xiv) maximum height;
(xv) maximum diameter (at breast height or root collar);
(xvi) height sums of squares;
(xvii) diameter (at breast height or root collar) sums of squares;
(xviii) height kurtosis coefficient;
(xix) diameter (at breast height or root collar) kurtosis coefficient;
(xx) height skewness coefficient;
(xxi) diameter (at breast height or root collar) skewness coefficient;
(xxii) number of missing tree height measurements;
(xxiii) dummy variable denoting whether the stand had been thinned at the time of measurement;
(xxiv) sum of the height measurements;
(xxv) sum of the diameter (at breast height or root collar) measurements;
(xxvi) sum of height and diameter (at breast height or root collar) cross products;
(xxvii) number of diameter (at breast height or root collar) measurements;
(xxviii) dummy variable denoting whether or not the stand had been pruned prior to the time of measurement;
(xxix) dummy variable denoting whether or not the stand had been either refertilised (or the fertiliser had been of a slow release type, such as rock phosphate);
(xxx) number of stems immediately after planting;
(xxxi) proportion of trees planted which survived through to the time of measurement;
(xxxii) mean height of seedlings immediately after planting;

As each record was added, the mean heights and diameters[1], maximum and minimum heights and diameters were compared with data from plots with similarly sized trees. In some cases, unusually large or small values led to a re-examination of the original data sheets, and to the correction of punching errors in the raw data files, followed by a recomputation of the complete record. No data were deleted, however.

3.1.2 Data Used for Initial Growth Modelling

In addition to the 27 experiments used to build a size-class distribution model of radiata pine between ages 0 and 5 in the Central North Island, three more in the region were later used for model validation. The locations of the experiments are shown in Fig. 3. The experiments were all randomised complete block designs, containing 10 trees per plot, except for one experiment, which contained five trees per plot. A separate catalogue of these experiments was created which specified, for each plot, altitude, longitude, latitude, distance from the sea, average annual rainfall (at the nearest New Zealand Meteorological Service (NZMS) rainfall station), average annual temperature (at nearest NZMS meteorological station), soil type, soil fertility (as rated by the Department of Scientific and Industrial Research

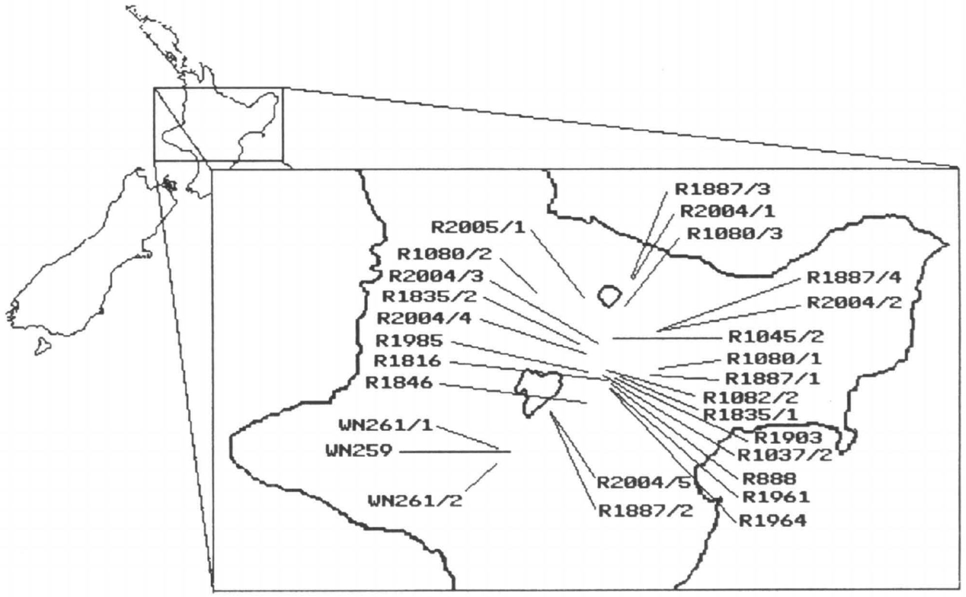


Fig. 3. Locations of experiments used for development of the initial growth model for the Central North Island of New Zealand.

---

[1] Diameters were sometimes at breast height and sometimes at root collar, depending on the heights of the trees. Variables in fields with this description contained either *dbhob* or root collar diameter measurements, depending on the value of dummy variable viii.

Table 1. Experiments used for analysis of initial growth.

Experiment I.D.	Altitude (m)	Factor levels Weed Control	 Cultivation	 Fertilisation	Age when measured Height	 Root Collar diameter	 *dbhob*
Wn259	951	1	1,0	0	0–4,6,7	0–4,6	7
Wn261/1	1062	1	1,0	N*P,0	0–2,4,6	0–2,4,6	
Wn261/2	686	1	1,0	N*P,0	0–2,4	0–2,4	
R888	604	1	1,0	0	0–3	0–3	
R1037/2	632	1	1	0	0–4	0–4	
R1045/2	532	1	1,0	0	0–3	0–3	
R1080/1	503	1	0	N+P,0	0–5		4,5
R1080/2	168	1,0	0	N+P,0	0–5		4,5
R1080/3	305	1,0	0	N+P,0	0–5		4,5
R1082/2	625	1	1,0	0	0–3	0–3	
R1816	603	1	1	0	0–3	0–3	
R1835/1	591	1	1,0	N+P,0	0–5	0–3	4,5
R1835/2	457	1,0	1,0	0	0–5	0–3	4,5
R1846	762	1,0	1,0	N+P,0	0–6	0–5	6
R1887/1	457	1	0	0	0–4		4
R1887/2	590	1	0	N+P	0–4		4
R1887/3	300	1	0	0	0–3		
R1887/4	435	1	0	0	0–6		5–7
R1903	600	1	1	0	0–3	0–3	
R1961	640	1	1,0	0	0–3,5	0–3,5	
R1964	640	1	1,0	N*P,0	0,2,4	0,2,4	
R1985	615	1	1,0	N*P,0	0,2,4	0,2,4	
R2004/1	370	1	0	0	0–2		
R2004/2	430	1	0	0	0–3		
R2004/3	370	1	0	0	0–2		
R2004/4	350	0	1	0	0–4		
R2005/1	360	1	0	0	0–3		

(1954, 1968) Soil Bureau (DSIR)), soil drainage (DSIR), response to phosphate (DSIR), total nitrogen (DSIR), percent clay (DSIR), cation exchange capacity (DSIR), pH (DSIR), and the nature of the topography (flat, medium slope, high slope). All the soils were of pumice origin, loamy or gravelly sands, and well drained. Relevant site variables, treatments, and ages of measurements are shown in Table 1.

Measurements taken after pruning or thinning were excluded from the analysis, as too few post-pruning and -thinning measurements were available.

Two of the experiments were designed to determine the effects of different initial spacings. Initial stockings represented in the data ranged from 200 to 4444 stems/ha.

Mean rainfall at the closest rainfall stations varied between 895 and 2019 mm/annum, while mean annual temperatures at the closest meteorological stations ranged between 7.8 and 12.5 degrees Celsius. Planting in all experiments on potentially frosty sites had been conducted late in the planting seasons.

3.2 Modelling Methodology

Modelling was conducted with SAS (SAS Institute Inc., 1985) on a Digital VAX computer system. The main analytical procedures used were GLM for linear regression models, NLIN for non-linear models, UNIVARIATE for analysis of residuals, and PLOT for graphical portrayals.

The repeated measurements within plots lacked statistical independence so their analyses, in conventional form, would result in under-estimations of residual mean squares. Emphasis was placed, therefore, on the elimination of bias in fitting model coefficients, and on attaining a distribution of residuals as close as possible to a normal one using procedure UNIVARIATE. This last procedure includes reports of residual skewness, kurtosis, and a Kolmogorov-Smirnoff graph, indicating the departure from normality. In addition, the mean of the residuals was reported, which would be expected to be close to 0 if the model were unbiased. A residual mean of 0 can be achieved, of course, even when the model is biased with respect to an independent variable, but graphical plots of residuals against independent variables were used to check for this eventuality. Coefficients in the models were sequentially added. At each stage, graphical plots of residuals against likely additional independent variables were examined for correlations, and as each independent variable was added, its interactions with other variables were tested.

3.3 Analyses of Individual Site Preparation Experiments

Lack of independence due to repeated measures meant that modelling with the complete Central North Island data set could not be used as a vehicle for testing hypotheses about differences in height, diameter (at breast height or root collar) and survival due to site preparation treatments. Analyses of individual site preparation experiments were therefore collated. In most instances, analyses had been conducted by designers of individual experiments, results from which were available in the form of unpublished reports. The analyses were inspected to ensure that appropriate statistical models had been employed or else new ones were conducted. From these, independent variables denoting site preparation likely to be useful in models for the entire region were identified.

Fourteen of the 27 experiments used for modelling contained direct comparisons between cultivation, weed control, and/or fertilisation treatments in designs which enabled valid statistical tests of differences in height, diameter, and/or survival among these treatments to be performed for any one year of measurement. The remainder either had inadequate replication for valid hypothesis testing, or were designed to test other treatments.

All the above 14 experiments were randomised complete block designs, 6 of which included factors laid out in a split plot arrangement. In these latter experiments, plots of cultivation treatment were split into alternative weed control and/or fertilisation treatments. All experiments were subjected to analyses of variance, with one analysis for each year's measurements of height and *dbhob* or root collar diameter. For each experiment, one of the following generalised models was used, depending on the exact experimental design:

$$X_{ijk} = \mu + M1_i + M2_j + (M1 + M2)_{ij} + B_k + \in_{ijk} \quad (17)$$

$$\begin{aligned} X_{ijkl} &= \mu + M_i + B_j + \in_{ij} + T1_k + T2_l + (M + T1)_{ik} \\ &+ (M + T2)_{il} + (T1 + T2)_{kl} + (M + T1 + T2)_{ikl} + \delta_{ijkl} \end{aligned} \quad (18)$$

where *M*, *M*1 or *M*2 denote mainplot treatments, and *T*1 and *T*2 denote subplot treatments. In some cases, only one mainplot or subplot treatment was relevant to this study and the terms referring to redundant treatment effects were therefore not included in the model.

Results from the individual experiments were tabulated. In five cases, the results were obtained from published papers, in another four from internal reports written by members of the Soils and Site Productivity section at the New Zealand Forest Research Institute, and the remaining experiments were analysed directly from raw data.

3.4 A Model of Initial Growth for the Central North Island

The analyses of individual site preparation experiments indicated treatments which could apparently be used as independent variables in a regional model of initial growth. Data from all 27 experiments were used to build models of survival, mean height and basal area/ha.

3.4.1 Seedling Survival

In a few cases, destructive sampling had been undertaken within plots for analyses of root growth. An adjustment to the denominator (normally N_0, the initial stems per plot) was required when survival proportions (S) were calculated for years after the date of sampling. The adjustment used was as follows:

$$N_{0n} = N_{0o}\frac{(N_{TD} - D)}{N_{TD}} \tag{19}$$

where N_{0n} = new denominator (S_T then became N_T/N_{0n}); N_{0o} = old denominator (initial number of trees in plot if there was no previous destructive sampling); N_{TD} = number of trees in the plot immediately before destructive sampling; and D = number of trees destructively sampled. This assumed that destructively sampled trees had a likelihood of dying equivalent to those trees which were not sampled.

Several survival (S_1 = survival at one age and S_2 = survival at next age of measurement) functions were tried in projection form, employing both proportional and absolute numbers of stems per unit area. A standard arcsine square root transformation was employed in all analyses involving proportions to adjust for bias in values near 1 or 0 (e.g.: Steele and Torrie, 1980).

(i) Anamorphic forms tested were:

$$S_2 = S_1 e^{(-\alpha(T_2^\beta - T_1^\beta))} \tag{20}$$

$$S_2 = S_1\left(\frac{T_1+1}{T_2+1}\right)^\alpha e^{-\alpha(T_2-T_1)} \tag{21}$$

$$S_2 = S_1^{\left(\frac{T_2+1}{T_1+1}\right)^\alpha} \tag{22}$$

$$S_2 = S_1\left(\frac{T_2+1}{T_1+1}\right)^\alpha \tag{23}$$

In each case the hypothesis was that α was a linear function of altitude, three dummy variables (weed control, cultivation, and site flatness), and their interactions. Equation 20 was also tested with “weed presence” substituted for the weed control dummy variable (i.e., if stand age for a given record was greater than the estimated duration of weed control, then weeds were assumed to be present). The yield form of Equation 20 was also evaluated:

$$S_T = -e^{\alpha T^\beta} \tag{24}$$

where S_T represents survival at stand age T.

(ii) Polymorphic forms tested were:

$$S_2 = S_1 e^{\beta(T_2-T_1)} + \alpha(1 - e^{\beta(T_2-T_1)}) \tag{25}$$

$$S_2 = (S_1^{-\beta} + \alpha(T_2^\gamma - T_1^\gamma))^{-\frac{1}{\beta}} \tag{26}$$

3.4.2 Mean Height

The following function was fitted to each treatment within each experiment:

$$\bar{h}_T = \bar{h}_0 + \alpha T^\beta \tag{27}$$

where h_0 = mean height immediately after planting and h_T = mean height at stand age T.

The regression coefficients pertaining to each treatment within experiments were then plotted against the following variables:

(i) altitude;
(ii) weed control;
(iii) ripping;
(iv) discing;
(v) phosphate fertilisation;
(vi) nitrogen fertilisation;
(vii) site flatness;
(viii) distance from the sea;
(ix) average rainfall at the nearest meteorological station.

Subsequently, Equation 27 was fitted to the entire data set, using proc NLIN, with parameters as linear functions of altitude and other combinations of the listed independent variables. The generalised model used was:

$$h_T = h_0 + (\alpha_0 + \alpha_1 V_1 + \ldots + \alpha_n V_n) T^{\beta_0 + \beta_1 V_1 + \ldots \beta_n V_n} \tag{28}$$

where $V_1..V_n$ were independent variables and their interactions, and $\alpha_0..\alpha_n$ and $\beta_0..\beta_n$ were estimated coefficients. A model was first estimated with only altitude included, then variables were subsequently added one by one, followed by their interactions if the estimated coefficients were significantly different from zero.

The projection form of Equation 28 was also tested, using independent predictors which appeared to be useful in the analysis with the function in yield form.

3.4.3 Basal Area

Basal area per hectare, where measurable, was calculated for each treatment within each experiment, and these values were plotted against the independent variables listed above (i to ix) , as well as against initial stocking.

The following function was fitted to all data, with the a regression coefficient as a linear function of altitude:

$$G_T = \alpha N_0 T^\beta \tag{29}$$

Another function was also examined:

$$G_T = (\alpha_0 + \alpha_1 V_1 + \ldots + \alpha_n V_n) N_0 T^\beta - N_0 k \tag{30}$$

Independent variables listed above were then tried, beginning with a model containing simply altitude, and adding other variables to form more complicated models.

Regression coefficients in the mean height function (27) estimated for each individual treatment within each experiment were matched with basal area data from each individual treatment within each experiment, and the time at which mean height equalled 1.40 m, $T_{G=0}$ was estimated for each record from:

$$T_{G=0} = \left(\frac{1.40 - \bar{h}_0}{\alpha}\right)^{\frac{1}{\beta}} \tag{31}$$

Using these estimates of $T_{G=0}$, the following function was fitted, with combinations of, and interactions between, the independent variables listed (i) to (ix) above:

$$G_T = (\alpha_0 + \alpha_1 V_1 + \ldots + \alpha_n V_n) N_0 T^\beta - (\alpha_0 + \alpha_1 V_1 + \ldots + \alpha_n V_n) N_0 T_{G=0}^\beta \tag{32}$$

In an attempt to utilise available root collar diameter data, the following function was fitted with the same independent variables as for the best fit of Function 32:

$$G_T = \frac{\alpha N_0 T^\beta}{DBH + RCD \cdot \gamma} - DBH(\alpha N_0 T_{G=0}^\beta) + RCD(G_0) \tag{33}$$

where

$$\alpha = (\alpha_0 + \alpha_1 V_1 + \ldots + \alpha_n V_n)$$

DBH and *RCD* were dummy variables indicating that diameter measurements had been taken either at breast height or root collar diameter, respectively, and G_0 was the root collar cross sectional area immediately after planting.

3.4.4 Distributions

In order to fit models from which parameters could be recovered for representing compatible size-class frequency distributions per unit area for height and *dbhob* at any age, functions of the same form as 28 were estimated with maximum height and height variance as dependent variables. Maximum *dbhob* was estimated with the following function:

$$Y_T = \alpha T^\beta - \alpha T_{Y=0}^\beta \tag{34}$$

where

$$\alpha = (\alpha_0 + \alpha_1 V_1 + \ldots + \alpha_n V_n)$$

Dbhob variance was estimated as a linear function of the independent variables listed previously and stand age.

The probability density function found to represent these distributions best was the reverse Weibull (Kuru *et al.* 1992). Predicted distributions were compared with those observed in the raw data, and appropriate percentiles of the extreme distributions were derived through trial and error.

3.4.5 Validation

Data from three additional experiments which had not been used to build the models just described were also available. The experiments were in Kaingaroa Forest, compartment 455 (611 m in altitude, weed control, no cultivation), compartment 552 (611 m in altitude, weed control, ripping and mounding), and compartment 542 (700 m in altitude, weed control, no cultivation). They were intended to compare alternative lifting and root trimming treatments, in which one treatment per experiment was useful for validation purposes. Annual height measurements from ages 0 to 4 were available from all experiments. *Dbhob* measurements were available from only compartment 455 at age 4. This validation set is obviously not entirely comprehensive but it provided some validation capability. It is hoped that a more comprehensive set of data suitable for validation might be obtained in future.

The mean height was calculated for each age, and the height distribution at age 4 was graphically plotted. These were compared with statistics predicted by the models described above for each site. The distribution of *dbhob* in compartment 455 was also compared graphically with the predicted distribution.

4 Results

4.1 Analyses of Individual Site Preparation Experiments

A summary of the results of hypothesis testing for site preparation experiments is shown in Table 2. In all cases, the null hypothesis was that there was no difference among treatments in survival, height, or diameter at the oldest pre-thinning and prepruning age of measurement within each experiment. In most cases, the null hypotheses were rejected at the p<0.01 level, but Table 2 includes some effects where the hypotheses were rejected at only the p<0.05 level.

The results for initial growth modelling can be summarised as follows:

(i) weed control consistently resulted in improved height and diameter growth and improved survival in some of the experiments;
(ii) cultivation often resulted in improved survival, and sometimes in improved height and diameter growth, while ripping and mounding together resulted in improved growth more consistently than did ripping alone;
(iii) fertilisation produced improvements in growth in only a minority of the experiments, and had

Table 2. Summary of hypothesis testing of site preparation effects from individual experiments.

Experiment	Age	Rip	Mound	Weed Control	P Fert.	N Fert.	P+N Fert.	Reference
WN259	6	n.s.	H D					EGM
WN261/1	6		H D S		H D	H D		SSP
WN261/2	6	n.s.			n.s.	n.s.		SSP
R888	3		H D S					EGM
R1080/1	5						D	GWp
R1080/2	5			H D S			n.s.	GWp
R1080/3	5			H D			n.s.	GWp
R1082/2	3	n.s.						EMp
R1835/1	5	S	n.s.				n.s.	EGM
R1835/2	5	H D S	H D S	H D				EGM
R1846	5			H D S			n.s.	EGM
R1961	5	H S						EMp
R1964	4	H S			n.s.	n.s.		SSP
R1985	4	H D	n.s.		n.s.	H D		SSP

The tabulated results should be interpreted as follows:
Age = Age of trees at which measurements were taken
H = Significant height increase
D = Significant diameter increase (root collar diameter or *dbhob*)
S = Significant survival increase
n.s. = No significant differences
blank = Not tested (alternatives not present in the experimental design)

Where an experiment contained both ripping and mounding treatments, and a significant mounding effect is indicated, the mounding treatment represented an improvement over and above the ripping treatment.
SSP = Analysis recorded in Forest Research Institute Project records
GWp = Analysis published (West 1984)
EMp = Analysis published (Mason and Cullen 1986)
EGM = Analysis performed for the purposes of this study by E.G. Mason

no apparent influence on tree survival;

(iv) interactions were significant in only two instances, one between weed control and cultivation, and the other between weed control and fertilisation.

No exact quantitative comparison of the magnitudes of the effects could be made without further modelling, as the hypotheses were tested at ages which varied from experiment to experiment. However, the effects of weed control on height and diameter growth were generally much larger and occurred more consistently than those of cultivation, which, in turn, were generally larger and more consistent than the effects of fertilisation.

4.2 A Model of Initial Growth for the Central North Island

4.2.1 Survival

Analyses revealed that the smallest residual mean squares and the least biased residuals were produced by fitting functions 20 and 24. The rate of mortality diminished with time in most plots, but mortality was higher during later years than during the first in one experiment in plots where weeds were not controlled. This resulted in the very uneven residual distribution shown in Fig. 4.

In general, the anamorphic functions represented early survival better than the polymorphic ones. The α parameter of Function 24 was related to several factors describing site quality and associated treatments. Survival decreased with altitude but the interaction between altitude and weed control was significant, with weed control improving survival to a greater extent at higher altitudes. The cultivation effect was independent of other factors, with ripping and/or mounding increasing survival.

There was an indication that mortality was greater on flat sites than on sloping sites, but data from trees grown on sloping ground were available only from high altitude sites. Including flatness as a variable in the model resulted in a poorly behaved pattern at lower altitudes. For this reason, flatness was not retained in the model finally adopted, but some recognition of such a possible effect may be needed in future studies.

4.2.2 Height

Equation 27 proved the best fit to the height data. Fig. 5 shows the distribution of residuals for all observations when a separate function was fitted for each treatment within each experiment. Most of the residuals were less than ±10 cm, and none exceeded ±25 cm. Graphs of the model coefficients vs. altitude (Fig. 6) showed a declining linear relationship up to 760 m, and a flattening beyond 760 m.

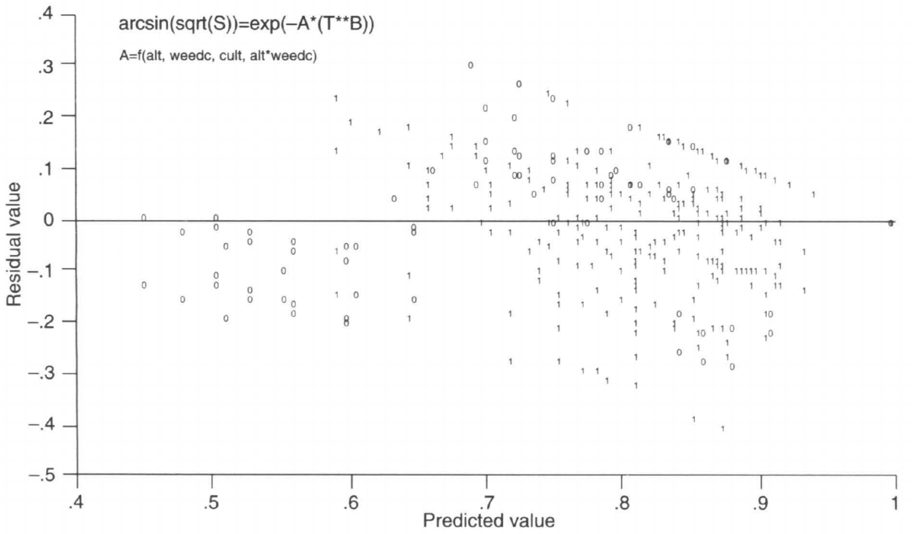


Fig. 4. Residual vs predicted values from the survival model selected. 1 = weed control, 0 = no weed control.

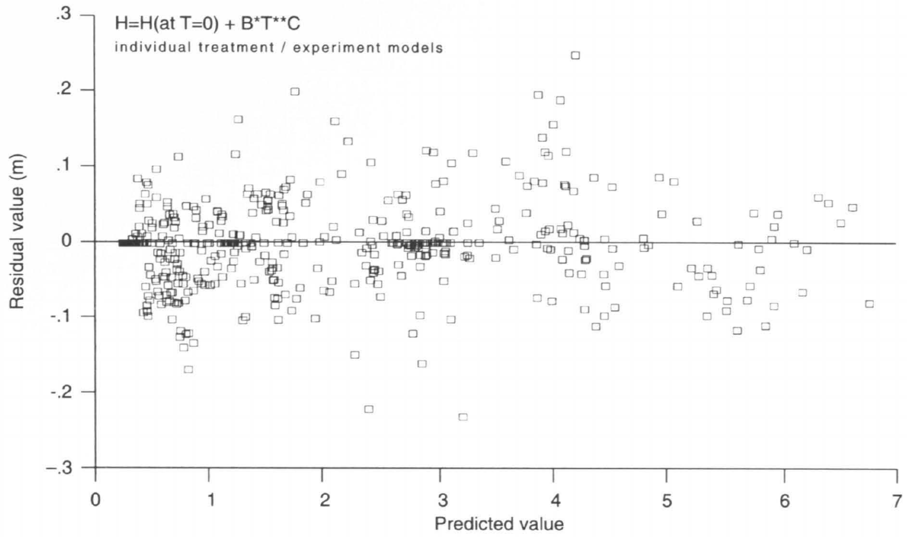


Fig. 5. Residual pattern from mean height models fitted to each treatment within an experiment individually.

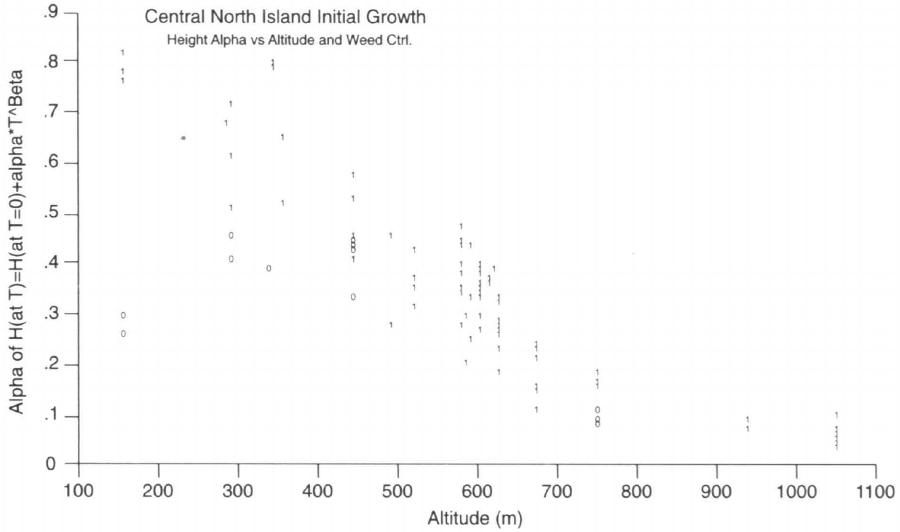


Fig. 6. The ralationship between the alpha parameters of height models estimated for each treatment/experiment and altitude. 1 = weed control, 0 = no weed control.

Multi-linear analyses showed that the α parameter of Equation 27 was clearly related to altitude, weed control, mounding, and the altitude times weed control interaction. The β parameter was related to altitude and weed control.

Results for one experiment, R2004/2, were

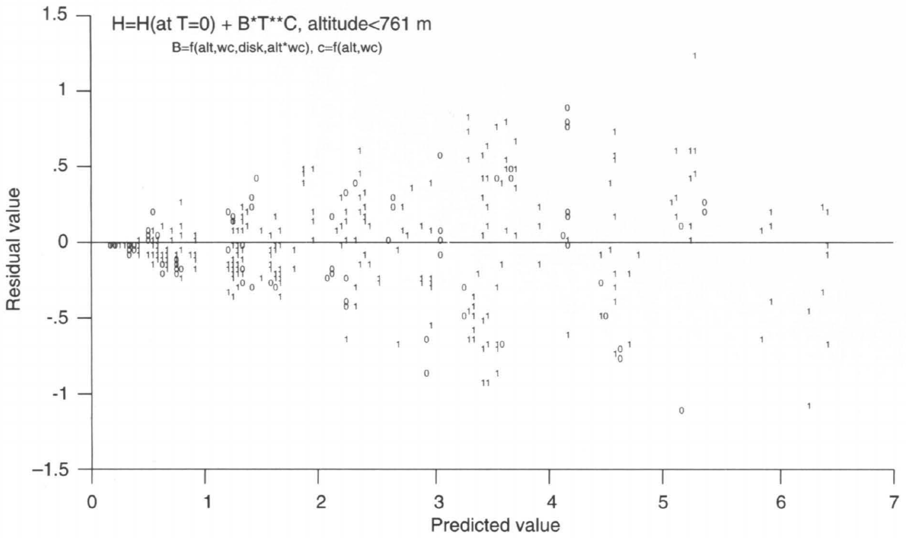


Fig. 7. Residual vs predicted values (in metres) for mean height model fitted for all data from experiments below 761 m altitude. 1 = weed control, 0 = no weed control.

anomalous. Coefficients estimated for the height model within this plot were not only outside the range expected for the location and treatments within the experiment, but had also an unusual combination of α and β parameter values. Inquiry with the controller of the experiment (M. I. Menzies, Scientist at the NZ Forest Research Institute, pers. comm.) revealed that severe boron deficiency had been observed in the experiment after two years of growth, and the entire experiment had been fertilised with ulexite. The experiment was therefore excluded from all analyses.

Two other apparently significant independent variables were found in the analysis, but each was subsequently dropped. Distance of the experiment from the sea was often significant, but highly correlated with altitude. Height growth was depressed on flat sites, but retention of this discrete variable in the model could not be justified as the effect was exceedingly small.

A model was next fitted using procedure NLIN for Equation 27, with α as a function of altitude, weed control, mounding and the weed control times altitude interaction, and with β as a function of altitude and weed control. Experiments above 760 m altitude were excluded, as the relationship between altitude and the α parameter had been shown to be non-linear above this altitude (Fig. 6), and no formulation was found that could represent mean height both above and below 760 m altitude without biased residual distributions. Most of the residuals about the model were within ±0.5 m of the predictions (Fig. 7), and all except one were within ±1 m. Height increased with weed control, mounding, and diminishing altitude. The effect of weed control on height was greater at lower altitudes, but there was considerable variation associated with the plots subjected to differential weed competition (Fig. 6).

Transformations of altitude values were attempted, in order to incorporate the experiments above 760 m in the model. The inverse of altitude and the square of altitude proved the most promising, but both resulted in poor estimations at lower altitudes (Fig. 8).

Equation 28 was also fitted in projection form (with the same independent variables), using only the shortest available growth intervals. Coefficient values obtained were virtually identical to those obtained from a yield form, except that some of the coefficients had confidence intervals which encompassed zero.

Controllers of the experiments had generally guessed the number of weed-free years their control methods would guarantee. These guesses were used to fit a model in projection form which would

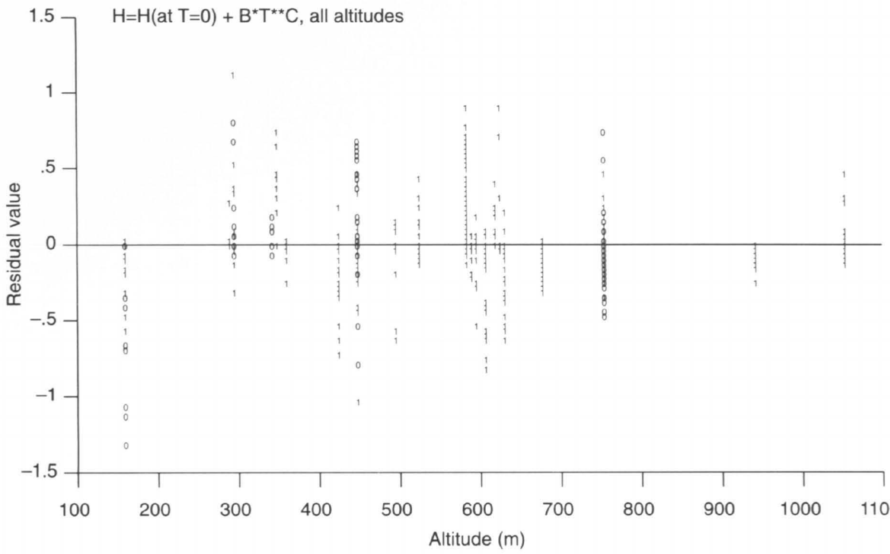


Fig. 8. Residual (m) vs altitude for mean height model estimated from all data. 1 = weed control, 0 = no weed control. B = f(altitude, weed control (WC), discing, and altitude *WC), C = f(altitude, WC).

be sensitive to re-introduction of weeds in plots where weed control had been implemented. The parameters associated with weed control in this model were small and insignificant.

In summary, Equation 28 fitted the data very well, with altitude, weed control, discing, and the weed control times altitude interaction being useful predictor variables. Predictions of growth would be more precise in the absence rather than in the presence of weeds. Data above 760 m altitude were excluded from the analysis, because their inclusion resulted in biased models. Initial height growth above 760 m in the Central North Island region should be a topic for further research.

4.2.3 Basal Area

The best fitting basal area/ha equation was 32. The α parameter of this function was related to the natural logarithm of altitude, weed control, and diammonium phosphate (DAP) fertilisation times weed control. As the last factor was not consistently significant in the analyses of individual experiments, the function was fitted without DAP fertilisation times weed control as well. The residuals were distributed within ±5 m^2/ha of the model (Fig. 9).

Equation 33 was fitted to all records with diameter measurements either at breast height or at the root collar. Independent variables included those for the model fitted to basal area only, plus mounding, weed control times altitude, and altitude squared. This last-named variable was needed because data above 760 m were included, and the relationship between basal area and altitude (for equivalent stocking) was no longer linear. Graphical plots of the residuals (Fig. 10) showed that the fit was poorer with respect to the basal area at breast height measurements for Equation 33 than for Equation 32.

To summarise, adjusting the intercept of the basal area function so that the model was compatible with the height model resulted in reasonable estimates of the basal area development of very young stands. Weed control, initial stocking and the natural logarithm of altitude, were included as independent variables. The DAP fertilisation times weed control factor was not expected to have an influence, and when included, its effect on the model was small. The model software has been built with two sets of parameters. One which in-

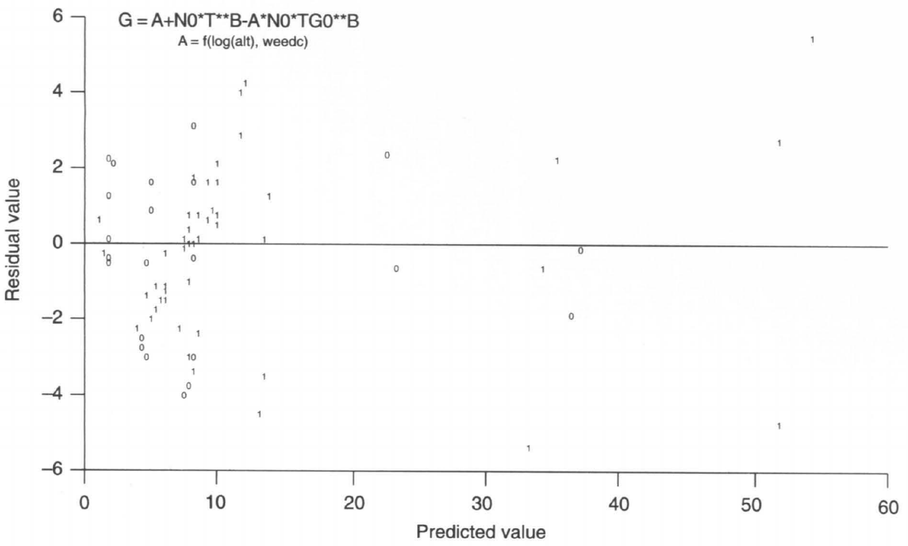


Fig. 9. Residual vs predicted values (in m²/ha) for basal area/ha model. 1 = weed control, 0 = no weed control.

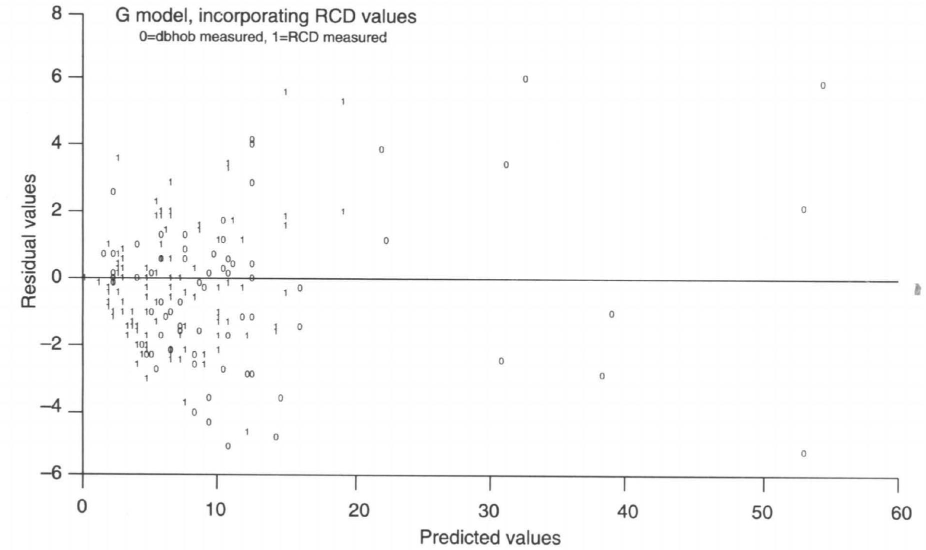


Fig. 10. Residual vs predicted values (m²/ha) for the basal area/ha model estimated with values calculated from both *dbhob* and RCD measurements. *A* = f(log(altitude) (ALT), weed control (WC), ALT*WC, disk).

cludes the effect of DAP fertilisation times weed control and the other which excludes it. Either model was less precise overall than the height model, because fewer *dbhob* data than height data were available. The attempt made to use root collar diameter and *dbhob* data jointly in a function which implied a linear relation between basal area and root collar cross sectional area, produced a less precise model than the one estimated from basal area data only.

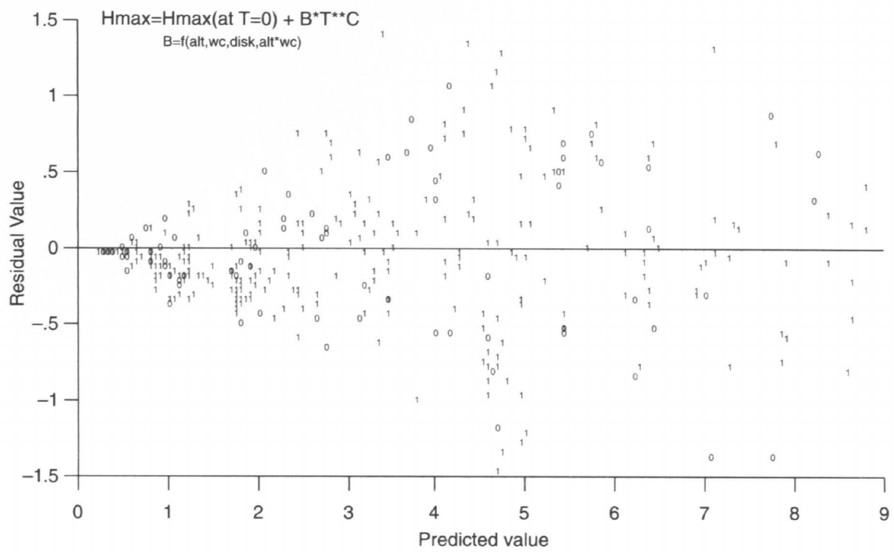


Fig. 11. Residual vs predicted values (m) for maximum height model. 1 = weed control, 0 = no weed control.

4.2.4 Height Distribution Models

Maximum height was well represented by Equation 28, with residuals all distributed within ±1.5 m of the model, and most within ±1.0 m (Fig. 11). The independent variables, altitude, weed control, mounding, and the altitude times weed control interaction for the equivalent of the α parameter of Equation 27 improved the predictions, as did the β parameter which was a function of altitude and weed control.

Height variance was also well represented by a function of the same form as 28, with coefficients related to altitude and weed control. The effect of weed control on height variance was particularly evident, with weed competition causing an increase in variation between trees.

The percentile of the Extreme Value Distribution (Liu Xu *et al.* 1992) employed for predicting maximum height was 96 %.

4.2.5 Diameter Distribution Models

Models of maximum *dbhob*, mean *dbhob*, and *dbhob* variance, the state variables necessary to characterise the reverse Weibull distribution, were much less precise than those of height, owing to the much reduced *dbhob* data set. For maximum *dbhob*, the α parameter of Equation 32 was related to the logarithm of altitude. Weed control was also included, for compatibility with the model of basal area. With two exceptions, the residuals were all distributed within ±2.0 cm of the model (Fig. 12).

Mean *dbhob* was also represented with Equation 32, and the α parameter was related to log(altitude), weed control, and log(altitude) times weed control. Mean *dbhob* was not used for representing the *dbhob* distribution, for reasons outlined below.

Dbhob variance was represented by a multi-linear function. It decreased with altitude and weed control, and increased with age and altitude times weed control. *Dbhob* variance decreased with initial stocking, but, although the confidence interval for the estimated coefficient excluded 0, no sound biological reason for the correlation was evident, so initial stocking was not used in the model finally adopted (Fig. 13).

When the diameter distribution parameters were recovered, it was found that more consistent representations of the distributions were obtainable by employing models of basal area, survival,

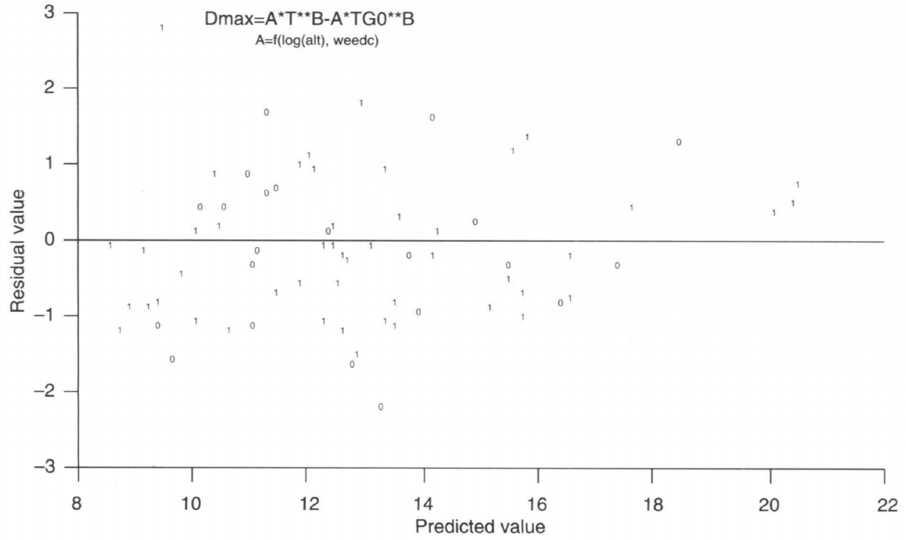


Fig. 12. Residual vs predicted values (cm) for maximum *dbhob* model, incorporating the time when maximum height reaches 1.40 m ($T_{G=0}$). 1 = weed control, 0 = no weed control.

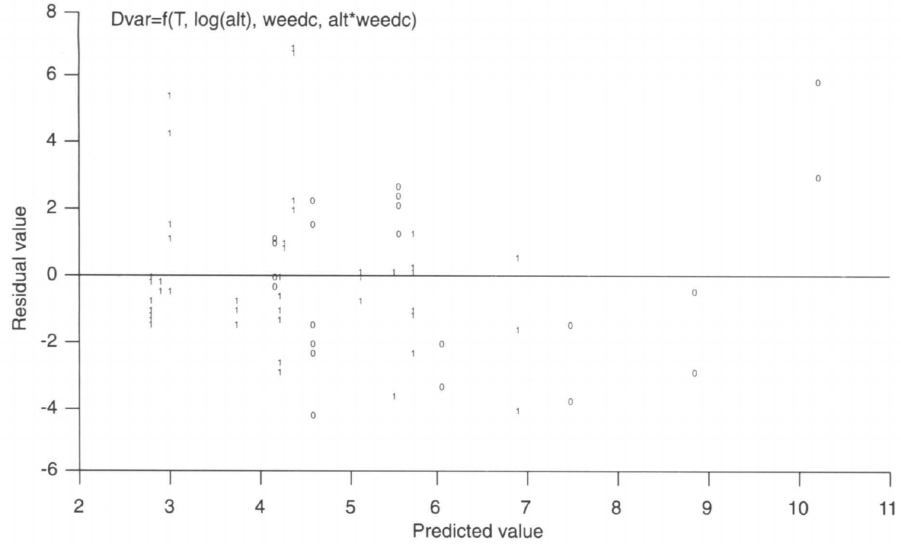


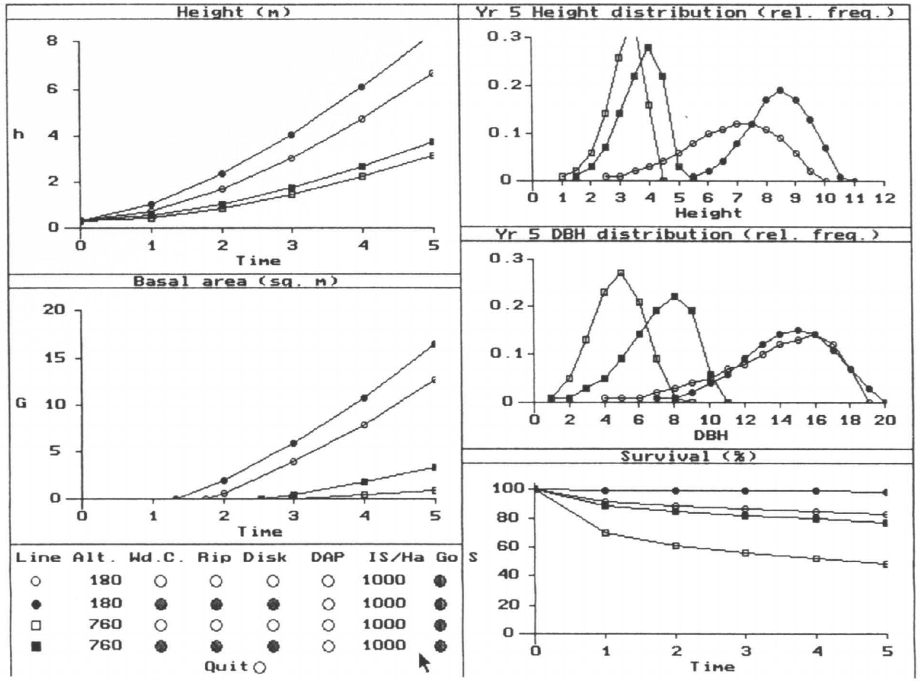
Fig. 13. Residual vs predicted values (cm) for multi-linear model of *dbhob* variance. = weed control, 0 = no weed control.

maximum *dbhob* and *dbhob* variance than when *dbhob* variance was recovered from the basal area and mean *dbhob* models.

The percentile of the Extreme Value Distribution employed for predictions of maximum *dbhob* was 95 %.

4.2.6 Software

The best fitting functions were represented in two computer programs written in PDC-PROLOG (Prolog Development Centre 1990), one for each of the DOS and Windows operating systems.



Line	Alt.	Wd.C.	Rip	Disk	DAP	IS/Ha	Go
○	180	○	○	○	○	1000	●
●	180	●	●	●	○	1000	●
□	760	○	○	○	○	1000	●
■	760	●	●	●	○	1000	●

Quit ○

Fig. 14. Sample screen from the initial growth model. Users nominate treatment using the control panel on the lower left. Any individual graph can be expanded to full screen size by clicking the title bar with the mouse.

Parameters of the height and diameter distributions were recovered from predicted stand statistics as described previously.

The programs were designed with graphical user interfaces which enable users to compare visually the predicted crop responses for alternative establishment strategies on different sites (Fig. 14), and to extract ASCII files with predicted responses in numerical form.

4.2.7 Validation

Graphs of predicted and observed mean height, height distribution, and *dbhob* distribution are shown in Figs 15, 16, and 17. Whilst the validation data sets were extremely limited, it was encouraging that the predictions of mean height and height distribution were very close to those observed. The diameter distribution prediction was poorer than that of height.

In compartment 542, the survival model underpredicted survival, as might be expected given the distribution of model residuals.

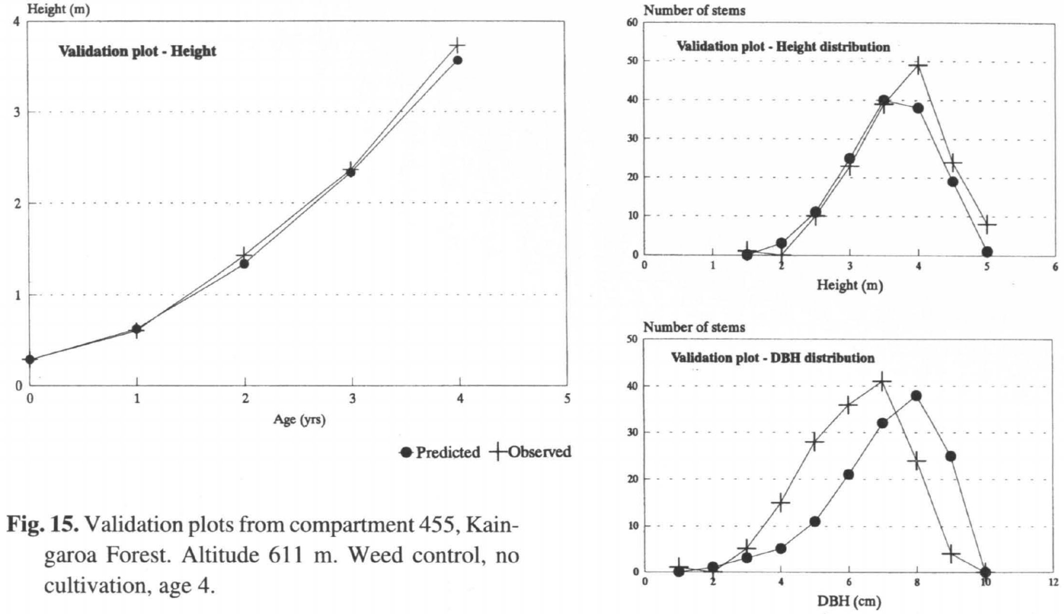


Fig. 15. Validation plots from compartment 455, Kaingaroa Forest. Altitude 611 m. Weed control, no cultivation, age 4.

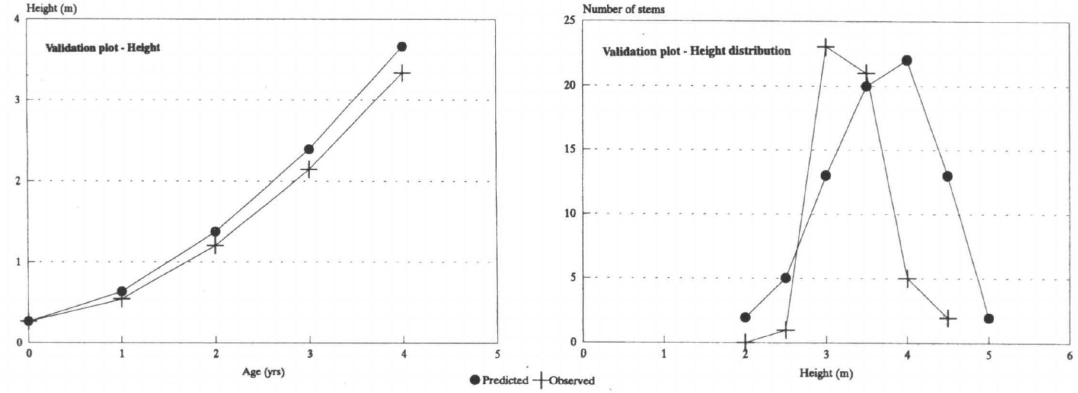


Fig. 16. Validation plots from compartment 552, Kaingaroa Forest. Altitude 611 m. Weed control, rip/disc, age 4.

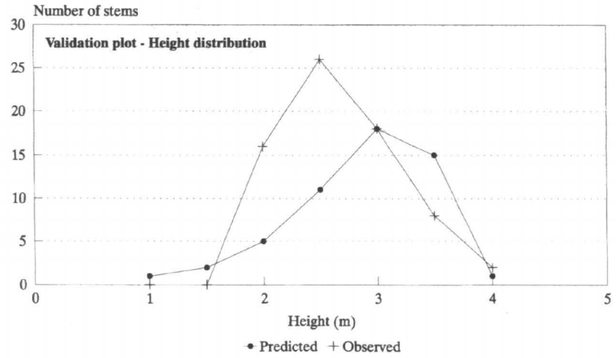


Fig. 17. Validation plot from compartment 542, Kaingaroa Forest. Altitude 700 m. Weed control, no cultivation, age 4.

5 Discussion

5.1 Analysis of Individual Experiments

The treatments which need to be included in a model of initial tree growth on pumice soils in the Central North Island were shown clearly through the analysis of individual experiments. Weed control appeared to improve survival and growth; cultivation appeared to improve survival of trees after planting; mounding appeared to improve growth; and fertilisation with phosphate and/or nitrogen did not appear to have any consistent effects. With appropriate soil analyses, it may have been possible to explain further the variation in responses to fertilisation.

More interactions were expected, especially between cultivation and weed control. With the exception of R1835/2, it had to be concluded that the effects of cultivation on these Central North Island sites were due to effects other than physical control of weeds.

Only some of the experiments were designed in ways which allowed conventional hypothesis testing of effects of site preparation. Identification of trends in residuals against all recorded site preparation treatments, therefore, was the main discriminating criterion for goodness of fit. Generally, visual and numerical evaluation of residuals using Proc UNIVARIATE confirmed the acceptability of the patterns of residuals, but survival models were erratic.

5.2 A Model of Initial Growth for the Central North Island

Development of the initial growth model described here has shown that it is possible to model the survival and growth of plantations immediately after planting across a region with due sensitivity to site productivity and site changes brought about by site preparation. The use of variables characterising sites rather than simply applying a conventional site index based on crop height shows how researchers can provide site-specific growth and yield models which managers would find useful now that Geographic Information Systems are providing accurate delineations of specific sites. They can then evaluate the cost-effectiveness of silvicultural treatments individually and collectively.

Use of the k adjustment factor for the growth of basal area when $G = 0$ has solved a problem which besets anyone attempting to fit traditional growth and yield functions to basal area data close to the age at which $G = 0$. That this resulted in compatible height and basal area functions was not only an added bonus, but a necessary condition for the modelling framework to be credible.

Models of distributions allow managers to estimate the effects of their actions on crop variability. However, at time of thinning, it is also important to know the numbers and sizes of trees with defects. Thus, future studies should address the question of mapping defects across the size-class distributions.

The characteristics of the individual component models developed, and the implications of the results for managers of plantations in the Central North Island region are discussed below.

5.2.1 Survival

The best-fitting model proved to be of anamorphic form, because the likelihood of mortality for individual trees was independent of stocking.

It was also expected that the best fit would be a form of the Weibull probability density function, with the likelihood of mortality diminishing as tree size increased. Factors contributing to mortality were likely to vary from year to year, however, which resulted in the difficulties experienced in attempting to eliminate bias from survival models estimated from such a small data set.

Greater mortality observed at high altitudes and in the presence of weeds could be attributed to more severe conditions experienced by trees, and the greater length of time they were subjected to severe conditions on account of their slower growth rates. Experiments located on frost-prone sites were planted towards the end of the planting season and this may also have had a confounding effect. It should be noted that planting earlier in the season on such sites would probably result in mortality greater than that predicted by the model.

Improved survival due to cultivation is less easy to explain. It is possible that cultivation resulted in more consistently good planting, or that cultivation facilitated root growth and improved access to water and nutrients.

Factors contributing to the likelihood of mortality for individual trees included:

(i) genotype;
(ii) physiological and morphological conditions caused by nursery treatment, some of which factors have been identified, especially spacing within nursery beds and conditioning regime employed (Menzies 1986);
(iii) handling during outplanting, the roughness of handling and the quality of planting being known to affect early growth and survival (Trewin and Cullen 1985);
(iv) specific conditions prevailing in the microsite surrounding the tree.

At a stand level, all these factors could have been included in the model if appropriate data had been recorded, but only factor (iv) was identifiable in the available data.

Factor (ii) might have been expected to have an influence on tree size at planting, and factors (iii) and (iv) would probably have affected tree size at subsequent re-measurements. Factor (iv) is also likely to have had greater influence on smaller trees. It is therefore possible that an individual tree approach to modelling survival, employing individual tree size as an independent variable, would yield an improved representation even with existing data.

Researchers have often found polymorphic models of survival to be superior to anamorphic ones after trees begin to compete. It is useful, therefore, to regard mortality in the few years following planting separately from that in later years after tree competition has set in.

5.2.2 Height

The exponential function used effectively represented the increase in mean height growth with increasing average tree size prior to the onset of between-tree competition. The fit within individual treatments in experiments was particularly good. Larger residuals produced by the model representing site preparation and site variation were due mostly to unexplained variation in site quality rather than any lack of fit of the basic function.

Other researchers have found that weed competition primarily affected diameter growth of young trees, unless the trees were overtopped by the weeds, in which case height was depressed (Lanner 1985, Zutter *et al.* 1986, Richardson 1991). It was therefore surprising that weed control was found here to have a strong influence on height and variance of height. Part of the explanation for this may be that weed cover decreases soil temperature and increases susceptibility to frost damage in the Central North Island (Washbourne 1978, Menzies and Chavasse 1982). In experiments elsewhere, the primary effects of weeds may have been to limit the availability of water, nutrients, and light to tree crops. Some of the largest effects of weeds were found in this study at low altitudes, however, and it is possible that the trees were overtopped in some of the plots containing weeds.

Whilst the mean height growth model predicts growth reliably in weed-free situations, there is clearly a need for a model sensitive to different weed species and levels of weed infestation. Data appropriate to such a refinement are currently being collected (B. Richardson pers. comm.).

Weed species and site occupancies are likely to change as growing trees occupy sites more fully, and coefficients of any model sensitive to different weed species and levels of infestation should be in projection form, with the level of competition at some point during the growth period as an independent variable. Nevertheless, the estimated coefficients of the height model in projection form were virtually identical to those estimated in yield form.

Reasons for the effect of mounding on height growth are subjects for conjecture. Washbourne (1978) suggested that a raised planting position might keep trees above the coldest air, which is commonly closest to ground level. Growth of loblolly pine in north eastern Florida was related to bed height (Outcault 1984), but the effects of bedding in Florida were probably due to improved drainage, as reported for slash pine on sites in Louisiana (Haywood 1983), and not to frost amelioration.

As mounding often results in a temporary destruction of weed cover, and the effects on growth may be partially due to frost, one might expect that there should be a significant interaction between cultivation and weed control. Such an interaction was observed in only one experiment, however. More complete descriptions of sites, and a database which included a greater range of site conditions might have allowed the estimation of an interaction within the model.

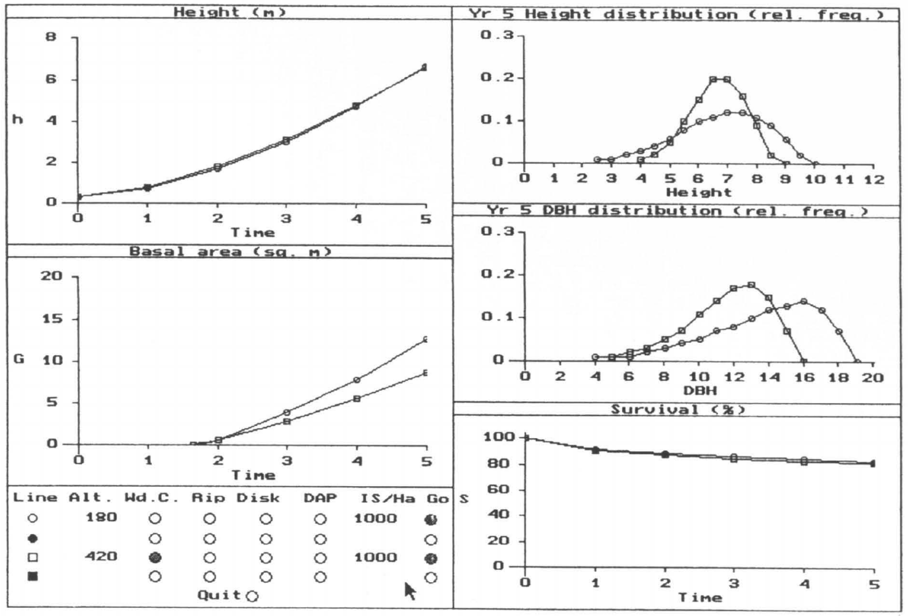
Site flatness was an important factor on some sites, with reduced growth on flat compared with sloping sites. Examples of large growth differences between trees on flat frost-prone sites and those on adjacent slopes in Kaingaroa Forest have been known for many years (Ure 1949). The reduction in growth was probably caused by frost. Limitations of the database, however, did not allow flatness to be included in the model. It should be noted that "less than a 3 degree slope" may be inadequate in defining frost prone sites, as the tops of hills may fit this description but be less frost-prone than depressions where cold air collects.

Initial stocking was found to have a detectable effect on height growth, but not nearly so marked as that observed in some Nelder experiments where height decreased with stocking below 2000 stems/ha (Mason 1992). There was no evidence of an interaction between initial stocking and weed control, and the smallness of the overall effect suggested that stocking was not worth being included in the model.

Comparisons of predicted and actual height growth of independent data used for validation showed an encouraging level of agreement, but a more thorough validation is obviously required. Survival, height, and *dbhob* data from temporary plots at a range of altitudes and with a variety of site preparation treatments would provide a check on model predictions. It should be noted that data used to construct the model came mainly from the vicinity of Kaingaroa Forest. Comparisons between model predictions and data from Kinleith Forest, to the west of the Kaingaroa region, suggest that growth of young crops is lower there and the model should not be used at Kinleith with its existing coefficients without some adjustment for these unexplained differences (Koesmarno, H.K., pers. comm.).

Traditionally, tree height growth has been regarded by forest growth modellers as independent of stand density (Husch *et al.* 1972), and it might be postulated that the mean height model estimated for young crops prior to crown closure represents the same process as height models of older crops, thus allowing the two to be interfaced smoothly. Ideally, at the age where a transition is made from one model to another, the two should have the same derivative, and so predict the same growth within any age range where they overlap. However, growth modelling in stands with actively competing trees differs markedly from that in young stands prior to crown closure. It is likely, therefore, that the models would predict similar, but different growth rates at equivalent ages, which would result in a modelling system which is not path-invariant if either of the models could be chosen between any two different ages.

Theoretical analyses involving the use of existing growth and yield models to predict rotation-length effects of treatments applied early in a rotation (Mason 1991, 1992, 1995) suggest that such predictions could be misleading. An analysis of connections between the model reported here and a model for older crops in Kaingaroa Forest has been reported elsewhere (Mason *et al.* 1997). In the Central North Island region, however, the effects of weed control might well diminish after crown closure. It is recommended that, until models sensitive to cultural practices and which utilise data from crops both prior to and after the onset of competition are developed, the change from the initial model to models of growth at older ages should be made at a fixed age within a decision-support system, at a time when the derivatives of the two models are as close as possible. Assumptions implied by the use of other



Line	Alt.	Wd.C.	Rip	Disk	DAP	IS/Ha	Go
○	180	○	○	○	○	1000	●
●		○	○	○	○		○
□	420	●	○	○	○	1000	●
■		○	○	○	○		○

Quit ○

Fig. 18. The effect of altitude on tree height/diameter ratio was different from the effect of weed control on height/diameter ratio, for stands of equivalent mean height and initial stocking.

models to compare effects of alternative cultural treatments at older ages should be made clear to users of the system.

5.2.3 *Diameter at Breast Height*

Far fewer *dbhob* than height data were available. The models estimated from *dbhob* measurements are consequently less precise than those estimated from height measurements. However, the functional form proposed and adopted for the studies described here successfully represented initial basal area growth without detectable bias and in a form compatible with the height function.

It should be noted that when mean height is 1.40 m, basal area would be non-zero, while *dbhob* is undefined at mean heights less than 1.40 m. With time, the frequency of trees passing 1.40 m in height would follow a near-normal distribution, and, while a proportion of trees remained below 1.40 m, the diameter distribution would appear as an upper slice of a near-normal distribution. This phenomenon could be represented by a different form of model if adequate measurements were available, but it is unlikely to be useful enough to be worth the effort. In a sense, the representation adopted in the models described here implies negative *dbhob* for trees with heights less than 1.40 m, with negative basal area/ha values as well. The use of the "*k*" term, defined as the time when mean height = 1.40 m improved the fit of the basal area and maximum *dbhob* functions in the years immediately after the entire stand had passed 1.40 m in height.

Since percentage mortality was unrelated to initial stocking, and the likelihood of mortality diminished smoothly with time, the estimated coefficients obtained for the basal area model incorporated the effects of greater mortality on some sites and with some treatments.

Basal area/ha development was affected differently by weeds than by altitude, for equivalent mean heights (Fig. 18). This provided further evidence that representing site quality with only height may be misleading.

If at any particular time more than a tiny proportion of the trees was smaller than 1.40 m in height, the *dbhob* distribution parameters could not be accurately recovered by the methods advocated here, nor could the actual distribution be accurately represented by a reverse Weibull function. In fact, no measurements of *dbhob* were available from stands where the height distribution included more than 5 % of trees below 1.40 m in height, and estimates of the diameter distribution, therefore, have been confined to ages 4 and 5 within the model program.

It is likely that estimation of *dbhob* variance through a multi-linear function was possible only because of the limited age range over which measurements were collected and because of the limited *dbhob* database. With a greater range of ages and more data, a function which was non-linear with respect to time might be expected to provide a better fit.

Using other basal area models to extend a comparison between cultural treatments beyond age 5 is subject not only to the same implications and limitations discussed for the extension of the height model using site index functions (Mason 1991, 1995), but also to other limitations. The initial basal area model uses initial stocking as an independent variable, while regional basal area projection functions sometimes imply that basal area/ha development at any given initial basal area/ha is independent of stocking. This latter implication may be justified after canopy closure, but it would be difficult to find an age at which the initial model of basal area development agreed with regional models over a range of stockings. In addition, basal area projection functions may or may not reflect site variation with any sensitivity. Another tool available in New Zealand, called the EARLY growth model (West *et al.* 1982) provides three "site qualities" for basal area projection, the choice of which to use being left to managers. There are currently no basal area projection functions for older ages in the Central North Island which use cultural treatments as independent variables. The implications of incorporating the initial basal area model into a rotation-length decision-support system containing other models depend on the features of the other models, but these should be made clear to users.

5.2.4 *The Effects of Increasing Altitude on Growth*

Survival and growth were found to be strongly correlated with altitude. Altitude is likely to be a key variable in the development of more sensitive growth models, as it is readily available to managers from maps and geographic information systems, and because several important growth-promoting factors tend to be related to it.

Norton (1985) found that monthly and seasonal minimum, maximum and mean temperatures in New Zealand could be predicted with a high degree of precision from altitude, distance of the site from the sea, and latitude. Reductions in growth with increasing altitude are likely to be partially due to decreasing temperatures with altitude. Temperature dependence is greater for physiological processes involving activation energies for chemical reactions, since higher proportions of molecules are likely to exceed any given activation energy as temperature increases. The rates of simple chemical reactions increase exponentially with temperature, but most biological reactions have a maximum rate at an optimum temperature, and decrease as temperature increases beyond the optimum. Reasons for this include changes to limiting reactions as temperature increases (with differing responses to varying temperature), differing responses to temperature of opposing reactions within a process, and, most importantly, a breakdown in enzyme catalysis as enzymes are denatured at high temperatures. Processes which integrate many individual components of plant physiology often vary approximately linearly with temperature over a wide range of temperatures (Jones 1983). This may partially explain why the relationship between model coefficients and altitude was found to be linear between 180 and 760 m.

Exposure to wind is likely to be greater at higher altitudes. Analysis of toppling within experiments showed an increase with altitude, suggesting that damaging winds were more frequent at higher altitudes in New Zealand (Mason 1992). Studies and reviews by Grace (1977) suggest that relative growth rates of plants increase with wind speed to an optimum, and then decline as wind strength increases beyond the optimum. Observed optima varied with species, but were generally less than 1 m/sec.

Decreasing partial pressures of carbon dioxide and water with altitude are further possible explanations for the observed reduction in growth with increasing altitude. Atmospheric pressure at 1000 m is 89 % of that encountered at sea level (Grace 1977). Controlled environment studies suggest that carbon dioxide concentration can limit photosynthesis (Moss *et al.* 1961), and artificial injections of added carbon dioxide has resulted in increased yields of field crops (Harper *et al.* 1973).

5.2.5 Modelling Improvement

The evident success achieved with this modelling indicates that forest managers are likely to have a useful tool available to them to assist substantially with decisions on what site preparation and seedling establishment procedures are economically worth implementing. There needs, however, to be more research on tree physiology and other biological aspects that complement the empirical mathematical modelling and allows it to be refined.

6 Conclusions

This research relates to radiata pine aged 0 to 5 years growing in the Central North Island of New Zealand. It has allowed the following conclusions to be drawn with respect to this population:

6.1 Mortality diminished with age, a trend which was modelled satisfactorily with a function derived from a Weibull probability density function:

$$S_T = e^{-\alpha T^{\beta}} \qquad (35)$$

6.2 Mortality was significantly related to:

- altitude – positively;
- weed control – controlling weeds resulted in lower mortality;
- cultivation – cultivation consistently resulted in a 10 % absolute increase in survival.

6.3 Mean height growth was able to be effectively modelled with a function of the form:

$$\bar{h}_T = \bar{h}_0 + \alpha T^{\beta} \qquad (36)$$

Residuals about the estimated model lay within ±0.1 m of coefficients if parameters were estimated for each individual treatment within an experiment.

6.4 Height development was significantly correlated with:

- altitude – linearly between 180 and 760 m, after which it diminished at a lower rate with increasing altitude;
- weed control – it was more rapid and crops were more uniform when weeds were controlled, increasing more at low than at high altitudes;
- cultivation with discs – disc cultivation resulted in small increases in growth.

Residuals from a function incorporating these additional effects lay within ±0.8 m of the predictions when one model was fitted to the entire dataset.

6.5 Basal area/ha growth was able to be represented with an exponential function, residuals about predictions from which lay within ±5 m^2/ha. Incorporation of the time to reach a height of 1.40 m (i.e. when $G = 0$, and estimated from the height function) in the form:

$$G_T = \alpha N_0 T^{\beta} - \alpha N_0 T^{\beta}_{G=0} \qquad (37)$$

- allowed estimates of growth capacity when $G = 0$ to be made over a range of site qualities;
- resulted in consistent height and basal area models, ie: $G = 0$ until $h > 1.40$ m.

6.6 Basal area/ha development was significantly related to:

- initial stocking – basal area increased with initial stocking;
- altitude – curvilinearly between 180 and 760 m, with growth diminishing at a lower rate with increasing altitude;
- weed control – growth was more rapid where weeds were controlled;
- the effect was greater at lower altitudes;

6.7 Compatible height and *dbhob* distributions of young radiata pine crops were able to be accurately represented by a reverse Weibull probability density function, with parameters recovered from models of mean height, maximum height, height variance, basal area/ha, maximum *dbhob*, and *dbhob* variance.

6.8 There was no apparent effect on early crop performance with nitrogen fertilisation. Correlations between growth and initial stocking, and between growth and site flatness were suggested by the analyses, but these trends could not be represented precisely enough by models estimated from the available data. A possible relationship between phosphate fertilisation and basal area/ha growth should be further investigated, since the experimental evidence to date is inconsistent.

References

Ballard, R. 1978a. Effect of slash and soil removal on the productivity of second rotation radiata pine on a pumice soil. New Zealand Journal of Forestry Science 8(2): 248–258.

Balneaves, J.M. & McCord, A.R. 1990. Gorse control: a trying experience at Ashley Forest. In: Bassett, C., Whitehouse, L.J. & Zabkiewicz, J.A. (eds). Proceedings of an international conference on "Alternatives to the chemical control of weeds". New Zealand Forest Research Institute Bulletin 155: 150–156.

Belli, K.L. 1987. FPES: A framework for modelling the artificial regeneration system. In: Ek, A.R., Shifley, S.R. & Burk, T.E. (eds.). Proceedings of the IUFRO symposium on Forest growth modelling and prediction, Minneapolis, Minnesota. USDA, Forest Service General Technical Report NC-120: 361–368.

— & Ek, A.R. 1988. Growth and survival modelling for planted conifers in the Great Lakes Region. Forest Science 34(2): 458–473.

Department of Scientific and Industrial Research. 1954. General survey of the soils of North Island, New Zealand. Soil Bureau Bulletin 5. 286 p.

Department of Scientific and Industrial Research. 1968. General survey of the soils of South Island, New Zealand. Soil Bureau Bulletin 27. 404 p.

Garcia, O. 1984. New class of growth models for even-aged stands: Pinus radiata in Golden Downs Forest. New Zealand Journal of Forestry Science 14(1): 65–88.

— 1988. Growth modelling – a (re)view. New Zealand Forestry 33(3): 14–17.

— 1990. The growth of thinned and pruned stands. In: James, R.N. & Tarlton, G.L. (Eds.). Proceedings of the IUFRO symposium on "New approaches to spacing and thinning in plantation forestry". Forest Research Institute Bulletin 151: 84–97.

— 1991. What is a diameter distribution? In: Proceedings of the IUFRO symposium on Integrated Forest Management Information Systems. Tsukuba, Japan, (in press).

Grace, J. 1977. Plant response to wind. Academic Press Inc., London. 204 p.

Haywood, J.D. 1983. Small topographic differences affect slash pine response to site preparation and fertilisation. Southern Journal of Applied Forestry 7(3): 145–148.

Hunter, I.R. & Skinner, M.F. 1986. Establishing radiata pine on the North Auckland podsols. New Zealand Forestry 31(3): 17–23.

Husch, B., Miller, C.I. & Beers, T.W. 1972. Forest mensuration. 2nd edition. Ronald Press Company, New York. 410 p.

Jones, H.G. 1983. Plants and microclimate. Cambridge University Press. 323 p.

Kuru, G.A., Whyte, A.G.D. & Woollons, R.C. 1992. Utility of reverse Weibull and extreme value density functions to refine diameter distribution growth estimates. Forest Ecology and Management 48: 165–174.

Lanner, R.M. 1985. On the intensitivity of height growth to spacing. Forest Ecology and Management 13: 143–148.

Liu Xu, Wood, G., Woollons, R.C. & Whyte, A.G.D. 1992. Stand table prediction with reverse Weibull and extreme value density functions: some theoretical considerations. Forest Ecology and Management 48: 175–178.

Mason, E.G. 1985. Causes of juvenile instability of Pinus radiata in New Zealand. New Zealand Journal of Forestry Science 15(3): 263–280.

— 1991. Establishment or regeneration decision framework for radiata pine in New Zealand. In: Menzies, M.I., Parrot, G.E. & Whitehouse, L.J. (eds.). Proceedings of the IUFRO symposium on "Efficiency of stand establishment operations", September 1989. New Zealand Forest Research Institute Bulletin 156: 366–377.

— 1992. Decision-support systems for establishing radiata pine plantations in the Central North Island of New Zealand. PhD Thesis, University of Canterbury, Christchurch, New Zealand. 301 p.

— 1995. Planning forest establishment operations with a computerised decision-support system: A case study analysis of decision-making over a full rotation. In: Proceedings of the 2nd International Vegetation Management Conference, New Zealand Forest Research Institute Bulletin.

— & Cullen, A.W.J. 1986. Machinery for forest establishment and silviculture. In: Levack, H. (Ed.). "Forestry Handbook". New Zealand Institute of Foresters. p. 60–62.

— , Whyte, A.G.D., Woollons, R.C. & Richardson, B. 1997. A model of the growth of juvenile radiata pine in the Central North Island of New Zealand: Links with older models, and rotation-length analyses of the effects of site preparation. Forest Ecology and management (in press).

Menzies, M.I. 1986. Nursery procedures for raising bare-root seedlings of radiata pine. In: Levack, H. (ed.) "Forestry Handbook". New Zealand Institute of Foresters. p. 48–49.

— 1988. Seedling quality and seedling specifications of radiata pine. What's new in forest research 171, Forest Research Institute, Private bag, Rotorua, New Zealand.

— & Chavasse, C.G.R. 1982. Establishment trials on frost-prone sites. New Zealand Journal of Forestry 27(1): 33–49.

Murphy, G. 1983. Pinus radiata survival, growth, and form four years after planting off and on skidtrails. New Zealand Journal of Forestry 28(2): 184–202.

Norton, D.A. 1985. A multivariate technique for estimating New Zealand temperature normals. Weather and Climate 5: 64–74.

Outcault, K.W. 1984. Influence of bed height on the growth of slash and loblolly pine in a Leon Fine Sand in Northeast Florida. Southern Journal of Applied Forestry 8(1): 29–31.

Payandeh, B. 1987. Plant: A model for artificial forest regeneration in Ontario. In: Ek, A.R., Shifley, S.R. & Burk, T.E. (Eds.). Proceedings of the IUFRO symposium on Forest growth modelling and prediction, Minneapolis, Minnesota, USDA, Forest Service General Technical Report NC-120. p. 386–393.

Preest, D.S. 1977. Long-term growth response of Douglas fir to weed control. New Zealand Journal of Forestry Science 7(3): 329–332.

— 1985. Chemical aids to planting site preparation. New Zealand Forest Service, Forest Research Institute Bulletin 100. 46 p.

Richardson, B. 1991. The effects of plant competition on the growth of radiata pine. In: Menzies, M.I., Parrot, G.E. & Whitehouse, L.J. (Eds.). Proceedings of the IUFRO symposium on "Efficiency of stand establishment operations", September 1989, New Zealand Forest Research Institute Bulletin 156: 242–249.

Shelbourne, C.J.A. 1986. The role of genetic improvement. In: Levack, H. (ed.). New Zealand Institute of Foresters Forestry Handbook. p. 44–45.

Snowdon, P. & Waring, H.D. 1984. Long-term nature of growth responses obtained to fertiliser and weed control applied at planting and their consequences for forest management. In: Proceedings of the IUFRO symposium on site and site productivity of fast growing plantations. Pretoria and Petermaritzberg, South Africa. p. 701–711.

Steele, R.G.D. & Torrie, J.H. 1980. Principles and procedures of statistics: A biometrical approach. McGraw Hill, 2nd Edition.

Trewin, A.R.D. & Cullen, A.W.J. 1985. A fully integrated system for planting bare-root seedlings of radiata pine in New Zealand. In: Proceedings of IUFRO symposium on "Nursery management practices for the southern pines". Montgomery, Alabama, USA.

— & Mason, E.G. 1991. Stand establishment research needs in New Zealand. In: Menzies, M.I., Parrot, G.E. & Whitehouse, L.J. (Eds.). Proceedings of the IUFRO symposium on "Efficiency of stand establishment operations". September 1989, New Zealand. Forest Research Institute Bulletin 156: 378–385.

— & Hunter, J.A.C. 1986. A containerised handling system for bare-rooted seedlings. In: Proceedings of the 18th IUFRO world congress, Ljubjana, Yugoslavia.

Ure, J. 1949. The natural regeneration of Pinus radiata in Kaingaroa Forest. New Zealand Forestry 6(1).

Vanclay, J.K. 1994. Modelling forest growth and yield. CAB International, United Kingdom.

Vincent, T.G. & Dunstan, J.S. 1989. Register of commercial seedlots issued by the New Zealand Forest Service. Ministry of Forestry, Forest Research Institute Bulletin 144. 155 p.

Washbourne, R.W. 1978. Establishment practice on frost-prone sites at Kaingaroa Forest. New Zealand Journal of Forestry 23(1): 107–120.

West, G.G., Knowles, R.L. & Keohler, A.R. 1982. Model to predict the effects of pruning and early thinning on the growth of radiata pine. NZ Forest Service, Forest Research Institute Bulletin 5. 35 p.

Whyte, A.G.D. & Woollons, R.C. 1990. Modelling stand growth of radiata pine thinned to varying densities. Canadian Journal of Forest Research 20: 1069–1076.

Wilhite, L.P. & Jones, E.P. Jr. 1981. Bedding effects in maturing slash pine stands. Southern Journal of Applied Forestry 5(1): 24–27.

Woollons, R.C., Whyte, A.G.D. & Mead, D.J. 1988. Long-term growth responses in Pinus radiata fertiliser experiments. New Zealand Journal of Forestry Science 18(2): 199–209.

Zutter, B.R., Glover, G.R. & Gjerstad, D.H. 1986. Effects of herbaceous weed control using herbicides on a young loblolly pine plantation. Forest Science 32(4): 882–899.

Total of 49 references

Submission of Manuscripts

Manuscripts should be submitted in triplicate to Acta Forestalia Fennica, Unioninkatu 40 A, FIN-00170 Helsinki, Finland. Detailed instructions to authors have last been printed in Acta Forestalia Fennica 244, are available from the editorial office, and can be found on Acta's WWW pages at http://www.metla.fi/publish/acta/

Publication Schedule

Acta Forestalia Fennica is published intermittently, 3 to 6 numbers per year.

Subscriptions and Exchange

Subscriptions and orders for back issues should be addressed to Academic Bookstore, Subscription Services, P.O. Box 23, FIN-00371 Helsinki, Finland, Phone +358 9 121 4242, Fax +358 9 121 4450. Subscription price for 1997 is 70 FIM per issue. Exchange inquiries should be addressed to the Finnish Society of Forest Science, Unioninkatu 40 B, FIN-00170 Helsinki, Finland, Phone +358 9 658 707, Fax +358 9 191 7619, E-mail sms@helsinki.fi

Statement of Publishers

Acta Forestalia Fennica has been published since 1913 by the Finnish Society of Forest Science. In 1989 Acta Forestalia Fennica was merged with Communicationes Instituti Forestalis Fenniae, started in 1919 by the Finnish Forest Research Institute. In the merger, the Society and Forest Research Institute became co-publishers of Acta Forestalia Fennica. The Finnish Society of Forest Science is a nonprofit organization founded in 1909 to promote forest research. The Finnish Forest Research Institute, founded in 1917, is a research organization financed by the Ministry of Agriculture and Forestry.

Abstracting

Articles in Acta Forestalia Fennica are abstracted and indexed in Agrindex, Biological Abstracts, Current Advances in Ecological Sciences, Current Advances in Plant Sciences, Ecological Abstracts, Forest Products Journal, Forestry Abstracts, International Bibliography of Periodical Literature, Life Sciences Collection.

ACTA FORESTALIA FENNICA
The Finnish Society of Forest Science
The Finnish Forest Research Institute

248 **Arto Rummukainen, Heikki Alanne** and **Esko Mikkonen:** Wood procurement in the pressure of change – Resource evaluation model till year 2010.

249 **Jukka Tyrväinen:** Wood and fiber properties of Norway spruce and its suitability for thermomechanical pulping.

250 **Mauno Pesonen, Arto Kettunen** and **Petri Räsänen:** Non-industrial private forest landowners' choices of timber management strategies: genetic algorithm in predicting potential cut.

251 **Jyrki Kangas, Teppo Loikkanen, Timo Pukkala** and **Jouni Pykäläinen:** A participatory approach to tactical forest planning.

252 **Pekka Ripatti:** Factors affecting partitioning of private forest holdings in Finland. A logit analysis.

253 **Vesa Kaarakka:** Management of bushland vegetation using rainwater harvesting in eastern Kenya.

254 **Pertti Hari, Juhan Ross** and **Marja Mecke (eds.):** Production process of Scots pine; geographical variation and models.

255 **Euan G. Mason** and **A. Graham D. Whyte:** Modelling initial survival and growth of radiata pine in New Zealand.

256 **Juha Nurmi:** Heating values of mature trees.

ISBN 951-40-1559-2
ISSN 0001-5636
9 789514 015595

ACTA FORESTALIA FENNICA 255 · 1997

Cover: Jarmo Koivunen