Carbon accounting: Forest growth rates and changing climates

Ministry of Agriculture and Forestry
Te Manatū Ahuwhenua, Ngāherehere

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Carbon Accounting: Forest Growth Rates and Changing Climates

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Report produced for MAF Policy under

CC MAF POL_2008-10 (110-1) Objective 3

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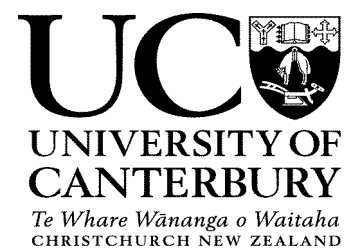
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Table of Contents

Executive Summary

Global climate changes may impinge on the future growth of New Zealand plantation forests. Since the latter represent a major export industry, it is clearly expedient to consider mechanisms by which any growth changes can be identified and estimated as to their magnitude.

Irrespective of the size of climatic change, it is by no means straightforward to suggest methodology that will satisfactorily estimate potential changes in forest growth. This is so, because:

(1)   More favourable weather conditions do not guarantee significant increased growth. Liebig's law suggests that many forest regions will be restrained by other limiting growth factors, for example nutrition.

(2)   Contemporary evidence was that carbon-dioxide levels are increasing and traditional thinking has been that this will result in faster plant growth. However, recent experiments at American universities question this. There is mounting evidence that in some years, additional tree growth is minimal, or trees quickly adapt to new environments, with only transient responses.

(3)   NIWA has produced estimates of climate change in New Zealand. These will necessarily be regarded as benchmark figures and essentially, known constants.

(4)   Any prediction of forest growth response will be associated with a significant risk factor.

(5)   Changes in climate will have impacts on soils, for example the depth of the A-Horizon. The sizes of these changes will need to be estimated. Recent work at the School of Forestry (SOF), Canterbury University suggests that current estimates of plant available soil water may be inappropriate for forest modelling.

There is a huge empirical *Pinus radiata* database of stand growth available in New Zealand to supply, in part, data necessary to construct models of forest growth through climate change. Concurrent and matching climatic data are available though electronic splined data layers, developed by Landcare and NIWA.

Forest modellers utilise sigmoidal-type yield equations to estimate stand yield. Adoption of the sigmoid shape is well justified empirically as well as being easily vindicated on physiological grounds.

Sigmoid yield equations are usually expressed in so-called projection form, where initial yield and a known age are included as predictor variables. The practice achieves substantial gains in precision, but the models are not ideal for climate/growth studies. Inclusion of initial yield, for example basal area/ha[7] as a predictor variable, tends to make other climatic

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[77] Basal area/ ha is an internationally adopted forestry expression for quantifying stand yield. Tree diameter is usually measured at 1.4 m above ground, so called DBH (Diameter at Breast Height). Assuming a circle, DBH can be expressed as an area. The sum of these areas for all trees occupying a stated area, but standardised to one hectare, defines basal area/ha.

predictors superfluous. Basal area is an excellent surrogate for stand production and is very closely correlated with future yield. Fortunately, projection equations can be modified to accommodate climatic predictors, referred to here as hybrid models.

Three published studies describing climate and growth models are briefly summarised. Two of these relate to specific localised areas utilising age, temperature, annual rainfall, or solar radiation as predictor variables. The third work[8] attempts a national growth model for *Pinus radiata*, using climatic variables. The paper describes methodology for circumventing the problem of initial yield masking climatic effects. Utilisation of stratification based on Landcare weather layers or utilising hybrid models involving solar radiation and available water potential, led to more efficient prediction compared to standard projection equations.

Two new climate-growth models have been prepared for this report. The first takes further an earlier study[9] looking at the prediction of stand top-height in terms of age and a set of topographic/climate predictor variables. A new basal area model for the North Island predicts net basal area/ha in terms of age, stems/ha, depth of the A-horizon and annual rainfall. An additional model predicts volume/ha in terms of top-height and basal area. The set of models are then applied to Central North Island (CNI) forests assuming small future increases in rainfall and A-horizon depth.

The second new study addresses CNI forests and represents a hybrid growth model approach. Mechanistic prediction models are constructed for top-height and basal area. Age variables are replaced by monthly accumulated light sums modified for temperature, recognising the minimum, optimum and maximum temperatures for photosynthesis.

NIWA has recently released estimates of likely changes in New Zealand weather conditions[10]. The main implications for Forestry are that average temperature will be 0.9^{o}C higher by 2040; by 2090 the figure is 2.1^{o}C. Rainfall forecasts are mixed. For the CNI, little change is predicted. Wind levels are expected to increase. No estimates are given for solar radiation or vapour pressure deficit.

The new hybrid model equations are utilised to estimate increases in productivity using the NIWA 2040 climate predictions. Extra volume in a 30 year rotation in the order of 70-100 m^3/ha is indicated but it is emphasised that these projections are subject to the full realisation of several assumptions.

This report has been developed in a short time frame and further work is desirable to produce more detailed and reliable estimates of productivity response through climate change.

These include the development of hybrid models in regions where rainfall changes are predicted. These models will require water balance models but recent surveys show current estimates of plant available water are unrealistic for forest soils. Further sampling over the

[8]Dzierzon, H. and Mason, E. G., 2006.
[9] Woollons *et al.*, 2002.
[10] Ministry for the Environment, 2008

country is required to calibrate current estimates. There is also an urgent need to reconcile the apparent differences between NIWA and Landcare climate data.

1. Introduction

1.1 Statement of topic

Global climate change is expected to bring changes to climate in New Zealand, which in turn may impact on growth rates of plantation forests. Plantation forestry is a major export industry for New Zealand, and impacts of climate change on forest productivity are therefore very important for the New Zealand economy.

The New Zealand Ministry of Agriculture and Forestry commissioned a pilot study of the impacts of climate change on plantation forest productivity. In addition, it is realised that if climate change affects productivity and forest growth patterns then new kinds of growth and yield models will be required for forest managers to reliably estimate outturns during plantation management.

1.2 Scope and limitations of study

The study described here is aimed at determining likely impacts of assumed values of climate change on plantation productivity. Estimates of climate change are taken as given and in particular, evaluation of the reliability of climate change estimates is beyond the scope of the study. Taking climate change estimates to be known data allows this study to focus on the relationships between climate and forest productivity.

2. Objectives

The objectives of this study are:

(a)   To produce a summary of available growth and climate data and to evaluate their quality and sufficiency for this study

(b)   Evaluation of quality of data in Geographical Information System layers describing soils, and re-measurement of soil properties in permanent sample plots if required.

(c)   Comparisons of models of plantation forest growth, sensitive to climate, using historical permanent sample plot measurements and to provide a summary of existent models.

(d)   Application of models to alternative climate change scenarios in New Zealand.

(e)   Provision of growth and yield models for forest managers that can be employed when climate is changing.

(f)   To suggest a framework where immediate research should be directed

3. Complications, Limitations and Restraints

Before embarking on summaries of available data it is prudent to list some factors that are likely to complicate the prediction of forest response to changing climate.

3.1 Liebig's law of the minimum

Liebig's law of the minimum (Sprengel, 1839) states that growth of a plant or population of plants will be enhanced by increasing the supply of the most limiting nutrient, and that adding other nutrients will have a negligible effect on growth. The 'law' however, has often been extended to include other growth inputs such as radiation, water, and ambient temperature. For example, in the conceptual equation below, the growth of the population O over time (T) is a function of the minimum of the influence of three inputs:

$$\frac{dO}{dT} = \min(f_1(radiation), f_2(water), f_3(temperature)) \qquad (3.1)$$

Liebig's law is very likely to have two implications for this study:

(1)   Prediction of increased growth in many New Zealand forests through more favourable weather conditions may not eventuate, or only a proportion of the responses may actually occur. What gains that might be achieved by some favourable climatic factors may be limited by nutritional or other deficiencies.

(2)   When a growth-promoting factor is represented in the equations, plant response to the factor may only be well represented within the range of growing conditions for which data were available during model fitting, and also strictly within the location(s) of the data. Climate change may well cause growing conditions to exceed the range of the dataset, leading to limitations of growth inputs not represented in the models, and thus causing bias.

3.2 Future effects of Carbon Dioxide

A prevailing view among scientists has been that climate change will prove beneficial to forests, at least in the short term. The argument is straightforward; plants need CO_2 to undergo photosynthesis so as to produce food and O_2. But with factories and cars emitting evermore carbon dioxide into the atmosphere, this will result in crops and trees to grow bigger and faster.

However, this scenario is challenged by results from large-scale field experiments at Duke (Duke University, 2004) and Stanford (Stanford University, 2004) Universities.

At Duke University, after exposing loblolly pine to enhanced levels of carbon dioxide for seven years, a complex pattern of results has emerged. While annual growth rates have increased by 10-25%, most of these have occurred only in dry years. Given normal or wet years, responses have been a lot less and may be the effect of inadequate nutrition.

At Stanford, results have been equally dramatic. A field experiment, involving four factors pertinent to climate change (carbon dioxide, temperature, rainfall and nitrogen soil levels) was created in 1999. The trial is capable of simulating double the concentration of current CO_2, a temperature rise of 2°F, a 50 % increase in rainfall and increased nitrogen deposition, and monitoring the effects of these on local plant-life.

A major finding has been that plant growth has only been stimulated with higher carbon dioxide when nitrogen, water and temperature were kept at normal (current) levels. When the latter factors were also elevated, plant growth was suppressed.

Studies of impacts of elevated CO_2 on growth of radiata pine have been conducted in large, open-topped containers at Bromley on the outskirts of Christchurch (Griffin *et al.,* 2000). Growth with CO_2 at 650 ppm was elevated during the first two years of the experiment compared to growth with CO_2 at 360 ppm, but then trees gradually 'acclimated', reducing stomatal conductance and thereby increasing water use efficiency. This increase in water use efficiency may explain the results at Duke University.

Results at Bromley may have been affected by the restriction of plants to relatively small containers, and by nitrogen supplies, according to a comprehensive review (Ainsworth and Long, 2005). Experiments with 'Free Air CO_2 Enrichment' (FACE) and comparisons with results from containerised CO_2 enrichment suggest that container experiments may over-estimate the degree of acclimation to elevated CO_2. The authors also assert that acclimation is more likely when nitrogen supplies are restricted, perhaps reflecting Leibig's law. Some experiments have resulted in up to 28% increases in productivity of forests. The authors also point out that responses of large trees to elevated CO_2 have not been tested.

We can conclude that responses of forests to elevated CO_2 are expected to be positive, but that uncertainty is high. Acclimation appears to be more likely when nitrogen is limited, and greater water use efficiency may mean that production would be more enhanced on dry sites. Measured responses to elevated CO_2 are large enough, however, that we cannot dismiss them, and more research is needed so that they might be better quantified.

Models presented in this report do not attempt to include the effects of CO_2 on tree growth.

3.3 Problems in the time domain

A problem exists as to how to reconcile any growth changes with respect to time. Current forest growth data has been essentially collected from 1960 onwards. For the corresponding period relevant climatic data are available, which can serve as 'bench-mark' statistics to compare against any future climate changes. Growth models can be constructed with current climate variables as predictor variables. Given estimates of climate change, the same models can be utilised to predict changes in growth.

Assuming a substantial proportion of any predicted growth response eventuates, a problem remains. When do these growth changes actually occur? For example, if best predictions are that rainfall and temperature will rise by stated amounts by, say 2040, it is simplistic to

assume that growth change will automatically follow over the same period, and that smaller incremental growth changes will occur in the shorter term. It could be that forests require minimum 'trigger' climate changes before responding and/or require a period of establishment in a new environment.

3.4 Implications for soils and water data

Several published growth models (for example, Woollons *et al.*, 2002) include soil variables as predictor variables. It follows that any alteration to the status of soil characteristics through climate change, may have significant implications for this study.

The soil A-horizon is clearly an important indicator variable, when considering potential growth changes through climatic activity. Containing the majority of humus and top soil, the layer is fundamental to tree growth. But the most important factor controlling the rate of top soil development is climate, consequently significant changes in the latter are likely to induce changes in tree growth rates. Higher rainfall and temperature should accelerate weathering processes, breaking down rock by chemical processes into soil. A major difficulty here will be to predict the extent and timing of changes in top soil status.

Water balance modeling requires good estimates of maximum and minimum plant available soil water. Data were obtained for a range of soil types from the Landcare Research New Zealand soil database (Newsome *et al.,* 2000). Estimates of soil texture and plant available soil water (PAW) were extracted for each permanent sample plot (see Section 4.1) location in the available database. Estimates of plant available water were made down to depths of visible roots or 900 mm, whichever the first, and so it was important to check whether plant available water estimates were valid for trees because tree roots can grow much deeper that 900 mm, and many surveys may have been conducted among shallow rooted plants such as grasses.

The results described here came from a pilot study of soils in Canterbury that will form part of a MForSc degree for Malte Coulmann, a current student.

3.4.1 Methods

Predominant soils currently under trees within the Selwyn Plantation Board Estate were visited. For each soil type holes were dug, and a face was cut to expose roots. Where roots extended further than the base of a hole (usually 1 m depth), cuttings at roadsides and windthrown trees were used to measure the depth of root growth. The texture of the soil was assessed subjectively (this will be done quantitatively at a later date), and the percentage of stones was also estimated. From these measurements, maximum and minimum plant available soil water was estimated for each soil type. In all 65 sites were visited for 8 soil types.

3.4.2 Results

Table 3.1 shows a comparison between values obtained from the Landcare database and measured plant available water for each soil.

Soil	Landcare PAW (mm)	Texture	Root depth (mm)	Estimated PAW (mm)
16	159	Sandy Loam	986	118
24H	29	Loam	1515	227
25e	159	Silt Loam	1057	190
29c	159	Silt Loam	950	171
29cH	159	Silt Loam	965	174
41a	189	Silt Loam	2300	414
57h	59	Loam	1200	180
57h+41aH	59	Loam	1341	201

Table 3.1 : Estimates of plant available water (PAW) from a database and from field measurements in forested land in Canterbury

In most cases the Landcare estimates of PAW are appreciably lower than estimates from field measurements, and this is partly due to tree roots exceeding the 900 mm maximum depth observed during soil surveys. This would lead to very large errors in estimation when a soil water balance model is run for a forest.

Coulmann's study will be extended by further field studies and by obtaining other researchers' field estimates of PAW for specific forested soil types around New Zealand.

4. Forest Growth Data

4.1 Background

New Zealand foresters have built up an extraordinarily large database of *Pinus radiata* growth and yield measures, with significant data going back to the 1930s (Woollons, 2000). It is undoubtedly the largest source of growth records for radiata pine in the World.

The methodology is simple. Demarcated plots are established at an early age (around 4-7 years) in forests, with the trees therein tagged and/ or numbered. Plot areas can vary from 0.04 to 0.2 hectares, usually with an additional buffer zone surround. The trees are periodically (1-4 years) measured for stem diameter and total tree height. Foresters utilise a stem diameter at 1.4 m above ground, referred to <u>diameter breast</u> <u>height, over-bark,</u> frequently abbreviated to DBH. There are no special growth dynamic reasons for choosing 1.4 m above the ground- it is universally utilised on convenience grounds. DBH is normally measured by a steel or cloth measurement tape, wrapping the tape around the circumference of a tree. The diameter of the stem is then estimated assuming tree girth is a perfect circle. The normal units are centimetres expressed to one decimal place.

A common measure of per hectare forest yield is basal area / ha (G) which is defined as:

$$G = 0.00007854 \sum_{i=1}^{n} DBH^2 \qquad (4.1)$$

where in (4.1)

n = number of trees in the sample plot.

(A per hectare estimate follows through division of the sample plot area)

Tree height is measured by inclinometers or laser equipped instruments. Not all trees in sample plots are explicitly measured for height. A sample of heights is acquired across the DBH range, then a regression model is constructed and the rest of the tree heights are estimated by prediction. The association between tree height and DBH is not especially strong but it is adequate.

A function of height that is frequently utilised by forest modellers is <u>mean-top-height</u> (H). It is defined as:

'The height predicted by a Petterson[11] height/DBH curve for a DBH corresponding to the quadratic mean DBH of the 100 largest trees per hectare (based on DBH) in a stand (Goulding, 1995).

Tree volume is estimated by a regression using DBH and tree height as predictor variables. The association between functions of DBH and tree height and volume is very strong.

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[11] $H = 1.4 + (\beta + \alpha/DBH)^{-2.5}$

5. Database

As at 1 April 2008 the School of Forestry (SOF) has a *Pinus radiata* database donated by Industry covering virtually all the plantations throughout New Zealand. These have been discussed by Dzierzon and Mason, 2006. Table 5.1 gives a brief summary of these data by Regions.

The abbreviation 'Meas' refers to the total number of measurements available for a particular region. The figures under the mean values are ranges.

AVERAGE VALUES

Region	Meas.	Age (years)	G/ ha (m^2)	H (m)	Vol/ ha (m^3)	stems/ha
Auckland	663	17 3-39	32 3-79	26 5-48	309 7-977	371 45-2030
Canterbury	2122	16 4-30	34 1-130	26 5-48	77 1-347	677 25-2300
Central NI	11580	18 1 -72	32 1-119	25 2-56	320 0-1789	488 30-8988
Hawkes Bay	1396	13 4-35	28 2-91	20 4-47	234 4-1244	488 42 -2525
Nelson Malb.	3393	16 2-48	26 1 -94	21 2-47	239 1-1234	465 13-4075
Northland	2434	14 4-33	22 1-98	19 2-45	181 1-1039	587 100-2625
Southland	3305	18 4-98	30 1-144	20 3-57	269 2-2094	450 62-3020
South NI	4016	16 3-41	29 1-145	21 2-49	263 1-1644	501 79-3016
S. Cant Otago	526	14 3-28	30 1-81	18 3-37	242 2-861	469 48-3416
Westland	2317	15 3-56	21 1-110	18 2-42	181 1-1100	433 20-3457

Table 5.1: Summary of growth data by regions

A grand total of 31 752 measures come from an overall total of 4927 sample plots. The huge number of data for the Central North Island is a legacy from the former Kaingaroa State Forest.

6. Climate Data

As of 1 April 2008 SOF has access to or usage of, two climate databases, one created by LANDCARE (Leathwick *et al*., 2002: Leathwick *et al*., 2003) and the other through NIWA.

Sample plot locations are defined by New Zealand Map Grid Easting and Northing; these are sufficient to obtain detailed climate statistics for any chosen site. The statistics are considered constants for any specific point location.

The two databases should give very similar values, especially for average annual values of fundamental variables such as temperature and rainfall. Unfortunately, initial analyses of data held by SOF have revealed some large and illogical discrepancies between the two bases. Figures 6.1 and 6.2 show plots of average annual rainfall and temperature from the two sources.
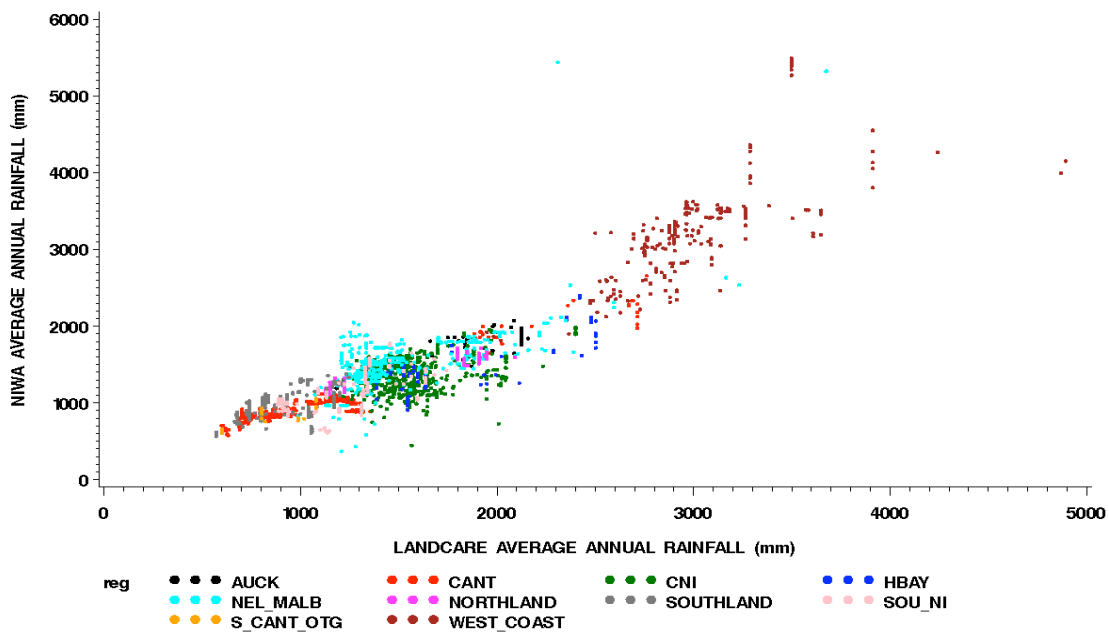
Figure 6.1: NIWA and Landcare rainfall estimates.

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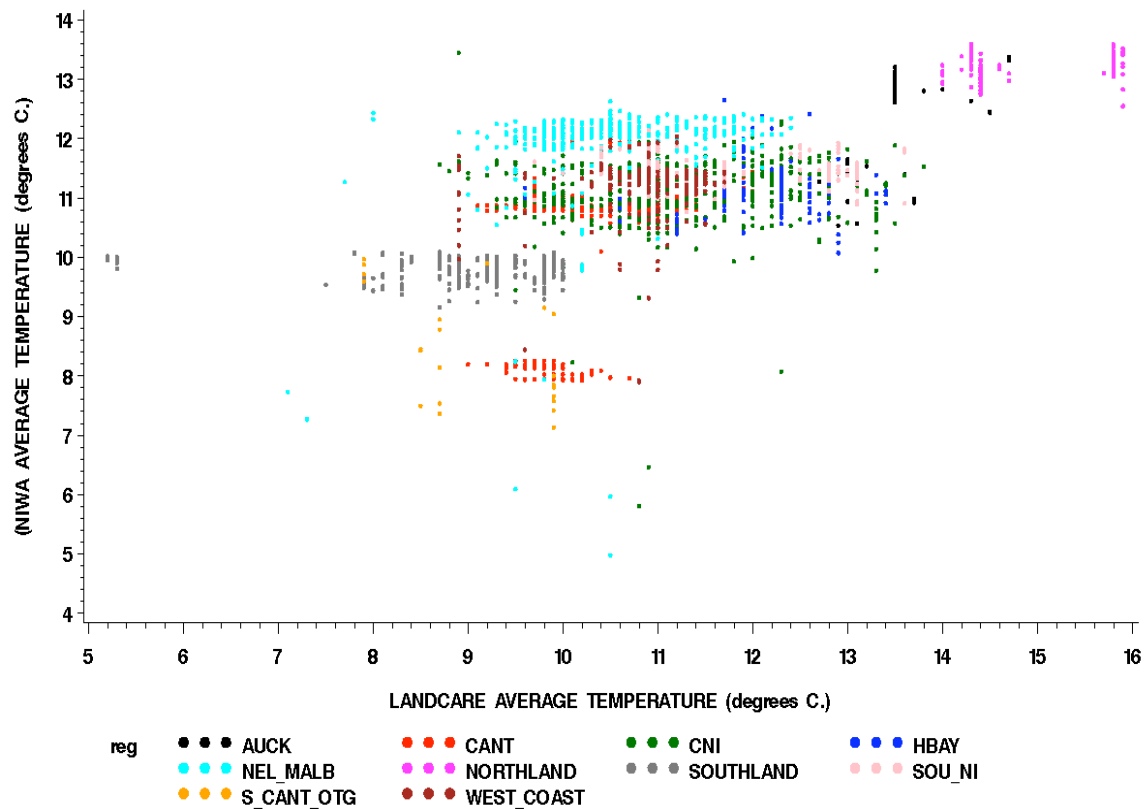
Figure 6.2: NIWA and LANDCARE temperature estimates

The relationship for annual rainfall is curvilinear and in the critical 1000-2000 mm range, values differ by as much as 250-300 mm. The temperature relationship is conspicuous for lack of association, with NIWA estimates seemingly truncated to virtual constants for specific regions. The reason(s) for these discrepancies are not currently understood. In the short time period we have had to produce this Report, it is inappropriate indeed injudicious to attempt new models based on these data. Obviously, it is a high priority to reconcile the differences between the two databases.

7. MODELS OF FOREST GROWTH

7.1 Two definitions

In what follows frequent references are made to the terms 'Yield' and 'Growth'.

'*Yield*' is a point estimate of standing growing stock at any given age. The response variable could be any of basal area/ ha, volume/ ha or tonnes C/ ha.

'*Growth*' refers to increment or change in yield, usually over a nominated time.

7.2 Introduction

Several alternative modelling options are available for representing impacts of climate change on plantation growth and yield. Growth is dependent on inputs of growth resources such as solar radiation, water, nutrients and ambient temperature. Many models currently employed in forestry use time (stand age) to represent cumulative inputs of growth resources on any given site, and are therefore difficult to adjust if climate changes. Explicitly including these growth resources leads to more complicated models that represent growth processes at a higher level of resolution.

The best level of resolution for growth and yield models has been much debated. Some researchers would prefer to see managers use highly complex models that describe physiological processes such as light interception, radiation use efficiency, carbon allocation, water use and nutrient uptake in detail. However, the more complicated a model is, the more likely it is to be biased because errors in sub-models and from multiple iterations of a model compound. Extremely complex physiological models can be too cumbersome for accurately predicting forest stand-level growth processes. Simpler, 'hybrid' models that include some elements of physiological detail offer potential for representing impacts of climate change on forest growth.

At the present time most plantation managers rely on highly abstract models loosely called 'growth and yield' models. Nevertheless, they have proven to be surprisingly accurate predictors of future forest yield. They are used primarily for making silvicultural decisions and for harvest planning.

7.3 Empirical Yield-Age equations

Forest growth is empirically depicted by sigmoid yield-age functions (Zeide, 1993). Differentiation of any such equation defines the corresponding growth curve.

The age of peak growth varies considerably by species, site and stocking. Figure 7.1 shows a plot of basal area increment against age, for two species, Radiata pine and Douglas Fir- both at around 400 stems/ha and growing on similar New Zealand sites. For *Pinus radiata*, the peak occurs early (age 12) and is characterised by a relatively sharp decline. In contrast, Douglas fir does not peak until age 17 but declines at a slower rate.
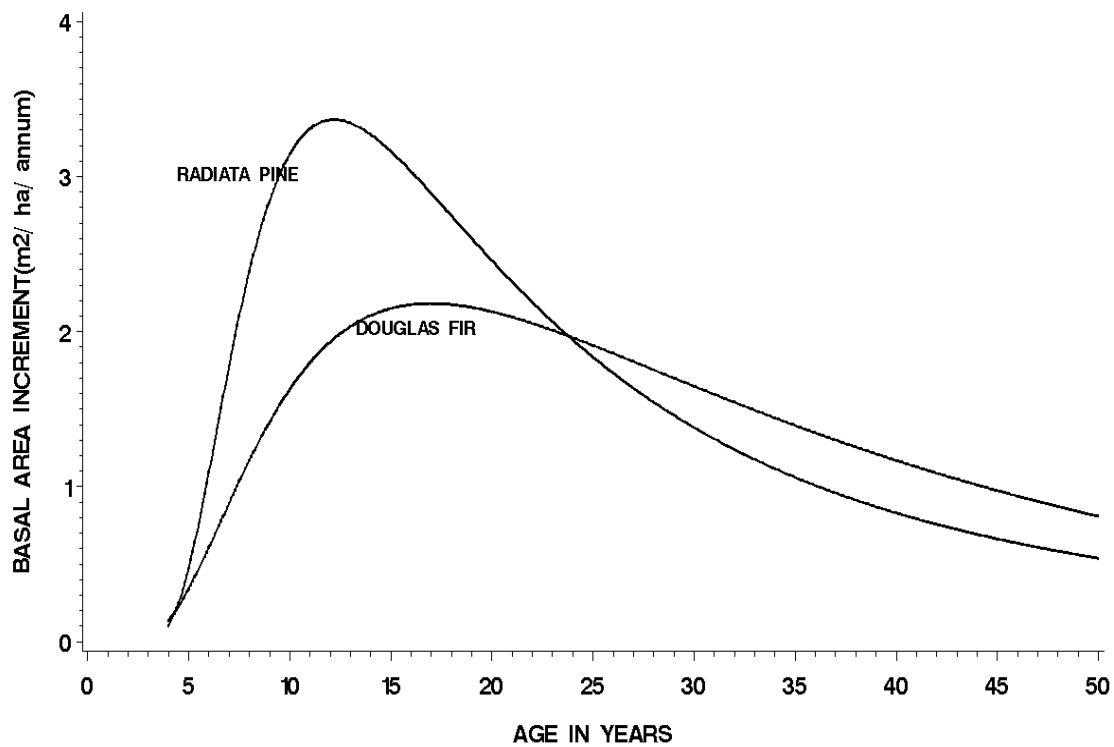
Figure 7.1: Growth rate of Radiata pine and Douglas Fir.

Forest modellers employ a variety of sigmoid equations to depict growth through time. Table 7.1 summarises some commonly utilised models.

Table 7.1: Sigmoid yield equations in forest research

<u>Log-reciprocal</u>
$$Y = \exp(\alpha + \beta / T^{\gamma})$$
(7.1)

<u>Chapman-Richards</u>
$$Y = \alpha(1 - \exp(-\beta T))^{\gamma}$$
(7.2)

<u>Hossfeld</u>
$$Y = \frac{\alpha T^{\gamma}}{(\alpha\beta + T^{\gamma})}$$
(7.3)

<u>Weibull</u>
$$Y = \alpha(1 - \beta \exp(-kT^{\gamma}))$$
(7.4)

<u>Monomolecular</u>
$$Y = \alpha(1 - \beta \exp(-\gamma T))$$
(7.5)

(Model 7.5 is strictly not a sigmoid function because it does not have a point of inflexion. However, many forestry datasets consist of a sequence of measures that begin after the peak of the stand growth so the equation can be useful)

<u>Note</u>: In Table 7.1 the parameter α symbolises an upper limit to yield, β is an intercept while γ and k represent rate (of growth) parameters.

Examples of their utilisation include Schumacher, 1939 (Log-reciprocal), Pienaar and Turnbull, 1973 (Chapman-Richards), Woollons *et al.*, 1990 (Hossfeld) and Yang *et al.*, 1978 (Weibull)

There are several relevant New Zealand studies for *Pinus radiata* where yield-age equations have been augmented or modified to include climatic variables. These are introduced in Section 8.0.

7.4 Projection Equations

The number of stems per hectare and the corresponding basal area per hectare are strongly related by definition (see equation 4.1). It is inevitable that when a range of stockings are grown through a rotation, a band of yield paths are produced, as shown in Figure 7.2. These data come from a thinning experiment, reported by Whyte and Woollons, 1990. If a yield equation is fitted to such data, the consequent precision of the estimates must be very low, since for a given age only one prediction is available.

To rectify this, forest growth modellers utilise so-called projection equations (Clutter *et al.,* 1992). They have a functional form:

$$Y = f(Y_1, T_1, T, \theta_i)$$
(7.6)

where in (7.6)

Y_1, T_1 = *a priori* known initial yield and age.
θ_i = model coefficients

Thus (7.6) is a yield equation but constrained in the manner shown.

Projection equations are fairly easily derived from their parent yield equations by integration and solving over defined limits (Y, Y_1) and (T, T_1). For any yield equation, two projection models can be derived, dependant on whether the asymptote parameter is retained or not in the equation. Projection equations including a common asymptote are referred to as being polymorphic (P); if not they are called anamorphic (A) equations. In practice, polymorphic forms are generally found to be better fitting models for stand variables such as top-height or basal area per hectare.
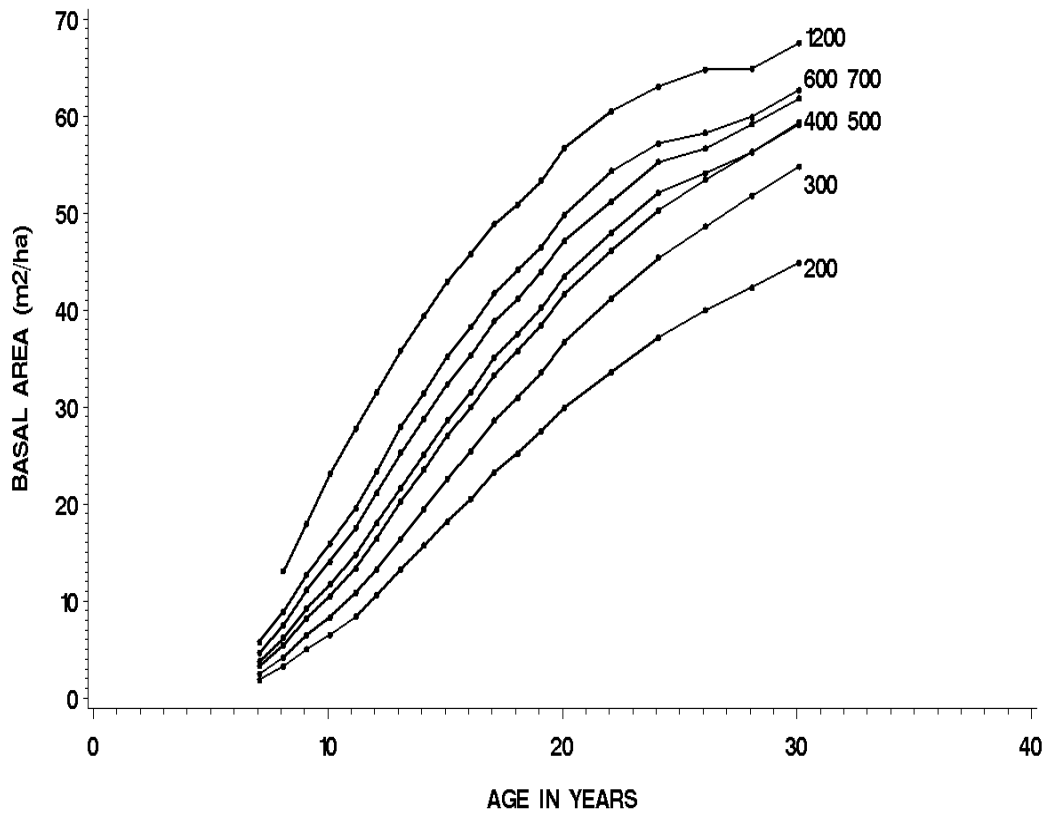
Figure 7.2: Basal area development from a thinning trial. The numbers refer to initial stockings.

The anamorphic and polymorphic projection equations for the yield models are summarised below.

Log-Reciprocal Equation

$$\ln(Y) = \ln(Y_1) + \beta \left(\frac{1}{T^\gamma} - \frac{1}{T_1^\gamma} \right) \qquad \text{(A)} \qquad (7.7)$$

$$\ln(Y) = \ln(Y_1) \left(\frac{T_1}{T} \right)^\gamma + \alpha \left(1 - \left(\frac{T_1}{T} \right)^\gamma \right) \qquad \text{(P)} \qquad (7.8)$$

Chapman-Richards Equation

$$Y = Y_1 \left(\frac{(1 - \exp(-\phi T_1))}{1 - \exp(-\phi T))} \right)^\varphi \qquad \text{(A)} \qquad (7.9)$$

$$Y = \alpha (1 - [1 - (Y_1/\alpha)^{(1/\gamma)}]^{(T/T_1)})^\gamma \qquad \text{(P)} \qquad (7.10)$$

Hossfeld Equation

$$\frac{1}{Y} = \frac{1}{Y_1} + \beta\left(\frac{1}{T^\gamma} - \frac{1}{T_1^\gamma}\right) \qquad \text{(A)} \qquad (7:11)$$

$$\frac{1}{Y} = \frac{1}{Y_1}\left(\frac{T_1}{T}\right)^\gamma + \frac{1}{\alpha}\left(1 - \left(\frac{T_1}{T}\right)^\gamma\right) \qquad \text{(P)} \qquad (7.12)$$

Weibull Equation

$$Y = Y_1 \frac{(1 - \beta\exp(-kT^\gamma))}{(1 - \beta\exp(-kT_1^\gamma))} \qquad \text{(A)} \qquad (7.13)$$

$$Y = \alpha - \beta[(\alpha - Y_1)/\beta]^{(T/T_1)^\gamma} \qquad \text{(P)} \qquad (7.14)$$

Monomolecular Equation

$$Y = Y_1\left(\frac{1 - \beta\exp(-\gamma T)}{1 - \beta\exp(-\gamma T_1)}\right) \qquad \text{(A)} \qquad (7.15)$$

$$Y = Y_1\exp(-\gamma(T - T_1)) + \alpha(1 - \exp(-\gamma(T - T_1))) \qquad \text{(P)} \qquad (7.16)$$

7.5 Hybrid models

While traditional growth and yield models are highly efficient and can be rigorously tested for bias and precision, they generally lack sensitivity to environmental factors that allow estimates of impacts of climate change on growth of crops on any given site. Hybrid models that are simplified models of physiological processes in forests offer a viable alternative.

7.5.1: Justification of sigmoid growth equations from a mechanistic viewpoint.

A sigmoid growth curve proposed by Von Bertalanffy (1957) is derived by considering growth as the difference between anabolic and catabolic processes, with anabolic processes some function of organism surface area, while catabolic processes are a function of organism volume. For animal growth, such a hypothesis can be justified, and it is proposed as a justification for the use of the curve in some forest growth and yield models (for example, Somers and Farrar, 1991). However, Richards (1959) explored the function, and pointed out that some of the most useful forms contained parameter estimates which were inconsistent with Von Bertalanffy's hypothesis. In any event, many of the most valuable parts of trees, especially heartwood, contribute little to catabolism, so representations of respiration as a function of total tree biomass are likely to be incorrect.

Plant dry matter production is generally a linear function of intercepted radiation (for example, Monteith, 1977; Biscoe and Gallagher 1975). It is therefore critical to be able to estimate the amount of radiation intercepted. This is generally called absorbed

photosynthetically active radiation, or APAR. Plants use visible light, which is at the peak of radiation intensity reaching the earth's surface from the sun.

Leaf Area Index (LAI) is defined as the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is dimensionless value, typically ranging from 0 for bare ground up to 20 for a dense forest. For conifers, it can be regarded as total needle surface area per unit ground area (Chen and Black, 1992)

At some maximum LAI, the canopy can be considered 'closed'. APAR has been measured for radiata pine in New Zealand (Grace *et al.*, 1987); intercepted radiation increased with increasing amounts of foliage, at least up to a leaf area index (LAI) of 3.5. Radiata pines' above-ground production increases approximately linearly with LAI values as high as 10, and showed a declining rate of increase up to LAI values of 20 or more in unthinned stands (Beets and Pollock, 1987), using LAI estimates computed using two-sided specific leaf area.

Models of production versus LAI need to account for attenuation of light by foliage that leads to lower levels of illumination deeper in a canopy. Beers law describes the interception of light by a homogeneous cloud of randomly distributed particles, and in the context of canopies is:

$$APAR = \phi(1 - e^{-\frac{kLAI}{\cos(\theta)}})$$

(7.17)

where in (7.17) the parameter ϕ is incoming PAR above the canopy, θ is the sun zenith angle, and k is a constant known as the extinction coefficient. In practice k is often about 0.5, but it will vary depending on the clumping of foliage within the canopy. Clumping of foliage violates the assumption of random distribution and introduces a bias into APAR estimates.

Hunter *et al.* (1987) found annual radiata pine bole volume increment/ha was linearly related to foliage mass and percent foliar nitrogen. This ignores light extinction, but highlights the critical importance of nitrogen as a raw material for chlorophyll. Research has shown that older foliage is generally less efficient at using APAR, and this is thought to be a consequence of lower levels of chlorophyll as N is re-translocated from old foliage to developing new foliage. For radiata pine, one and two year old foliage have been shown to be about 75% and 50% as quantum-efficient as new foliage respectively (Xu, 2000).

Growth in plant biomass should be the difference between matter created by photosynthesis and that consumed by respiration. Measurements of radiata pine stand respiration rate show a linear correlation with rate of photosynthesis (Beets, *pers. comm.*). This might be expected given that the surfaces involved in absorption of nutrients and production of photosynthate (fine roots and needles) are also those most involved with respiration, and their total volumes and surface areas might be

expected to be related linearly. This latter relationship is due to the approximately constant sizes of these parts, with increases in total volume or surface area related directly to their number. It should be noted, however, that the specific leaf area of radiata pine needles has been reported to decrease by more than 20% between tree ages 2 and 12, with most of the decrease occurring prior to age 8 (Beets and Lane, 1987), therefore LAI cannot be considered to be completely equivalent to foliage biomass at different ages.

When trees are first established, they occupy a small segment of a site, and their abilities to secure resources and intercept light are minimal. They therefore exhibit relatively modest growth rates. As young seedlings grow without between-tree competition, one might expect that biomass production should be a function of plant size, and that, given the allometric properties of stands, exponential functions should accurately represent mean height and basal area/ha. This would be due in part to correlations between sizes of different parts of a growing plant, known as 'allometric relationships'. In fact relative growth rate declines immediately after establishment (Britt *et al.*, 1991: Mason, 1992). Reasons for the decline appear to include self-shading as trees develop broader canopies, increasing proportions of older-aged foliage, changes in leaf shape, and changes in allocation patterns (Kirongo and Mason, 2003).

After a forest canopy has closed, it might be expected that growth rate should no longer increase, and that, given no changes in foliage efficiency or foliage carrying capacity, that biomass growth should be roughly linear over time. Foliage mass of radiata pine was reported to increase with age until an equilibrium level was reached (Madgwick *et al*., 1977), and the same was reported for Douglas fir (Long and Smith, 1984).

Models of radiata pine stand growth and yield in New Zealand show stands exhibiting exponential bole volume growth initially, or after thinning, with yields subsequently increasing roughly linearly with age, at least up to age 30 (Garcia 1984, 1990). However, this linearity cannot be entirely attributed to constant total biomass growth after canopies have closed, because partitioning of dry matter has been found to change with physiological age in studies of radiata pine aged between 2 and 12 years (Beets and Pollock, 1987). Total above-ground production at a given LAI was found to increase with age, and this was attributed to a shift in partitioning from roots to stem wood. In addition, relatively more dry matter production was invested in stem wood than leaves as stands aged.

In summary, sigmoid yield curves are appropriate in stand growth and yield models because stands increase in growth rate as a function of their increasing occupation of land area, and then reach maximum growth with the foliage carrying capacity of the stand. Leaf biomass may peak and then decline, or may possibly remain at equilibrium for a period of time. Subsequently, for poorly understood reasons, aging results in a decline in LAI and growth rate. For New Zealand radiata pine stands, at least in the Central North Island and Nelson regions, stand growth of stem volume initially increases, and then becomes approximately linear within usual rotation ages.

7.5.2 An example of a simplified physiological forest growth model

Landsberg and Waring, 1977 describe the construction of a mechanistic growth system, so called the 3-PG model.

Local microclimatic conditions modify crop growth by mediating light use. Net primary productivity (NPP) of a plant canopy has been found to be directly proportional to light interception (Monteith, 1977), and local microclimate affects the slope of the relationship between intercepted light and NPP. The 3-PG model explicitly represents this principle for forest crops by calculating soil water, vapour pressure deficit, temperature and fertility modifiers on use of intercepted photosynthetically active radiation. This model can be categorised under the general class of "radiation use efficiency" models.

The 3-PG model can be expressed as:

$$NPP \;=\; \varepsilon \sum_{t=1}^{T} APAR_t \, \min\{f_\theta \; f_D\} f_T \; f_F \; f_S \qquad\qquad (7.18)$$

where in (7.18)

NPP=net primary productivity, t = time interval (month), APAR=absorbed photosynthetically active radiation, ε = maximum quantum efficiency for a species, f_θ = soil water modifier (0-1), f_D = vapor pressure deficit modifier (0-1), f_T = temperature modifier (0-1), f_F = frost modifier (0-1), f_S = senescence modifier (0-1).

The model maintains a soil water balance using soil depth, soil type, rainfall, temperature, LAI and the Penman-Monteith equation for calculating evapotranspiration to calculate the soil water modifier. Most modifiers are calculated using models that represent underlying processes, such as the logarithmic decline of stomatal conductance with increasing vapour pressure deficit. The fertility modifier is simply a number chosen by the user.

Once NPP has been estimated for a given month, the amount of photosynthate used for respiration is calculated using a constant supplied by the user, and the rest is allocated to foliage, stems or roots. Allocation coefficients are estimated from measurements of allometry, assuming that lower fertility results in increased allocation to roots. The actual proportions allocated to these pools depend on coefficients supplied by the user that make allocation vary with tree diameter at breast height. Pinjuv *et al.* (2006) compared 3-PG with traditional mensurational models using a large PSP dataset in Canterbury, finding that the best mensurational model was more precise and less biased than 3-PG.

The 3-PG model has attracted plenty of interest, but it has a few characteristics that forest modellers usually try to avoid. It is not path invariant (Clutter, 1963; Clutter *et*

al., 1992), and it has many estimated parameters so that it might be fitted to the same dataset in a variety of ways and users need to fit parameters locally to sub-models so that the model will represent any given species in a particular location. Carbon allocation is derived from allometry, which may lead to slight biases in allocation, and estimating leaf area index can be problematic. The senescence modifier is *ad hoc*, and reflects the fact that senescence is poorly understood. In addition, it is highly recursive, so that errors may propagate when dependent variables from one month's simulation are used as independent variables during the next month. Clearly something in between traditional growth and yield modelling and 3-PG is more likely to allow precise estimates of impacts of climate change.

7.6 The concept of hybrid models

A synthesis of mensurational models and physiological approaches like 3-PG can be built by directly substituting 'potentially used radiation sum' for time in projection equations (Mason *et al.*, 2007).

With such a synthesis no attempt is made to directly measure APAR, nor is carbon allocation explicitly represented. Yield equations used for juvenile trees and sigmoid equations used for older crops implicitly represent effects of APAR and allocation on relative growth rate. Using modifiers such as those in the 3-PG model to assess what proportion of incoming light could potentially be used by plants if it were intercepted makes these hybrid equations sensitive to changes in growth resource availability that may be influenced by competing vegetation, changing sites, or varying weather patterns from year to year. Such a 'Potentially useable light sum' model was used by Mason *et al.* (2007) to represent growth of Douglas fir in a complicated experiment with weed control treatments that changed growing conditions in different plots in diverse ways. The potentially useable light term that was substituted for time was:

$$R_T = \sum_{t=1}^{T} R_t \min\left[f_\theta f_D\right] f_T f_{CI} \qquad (7.19)$$

where in (7.19)

R_t=radiation in month t
R_T=potentially useable light sum
f_θ=soil water modifier (0-1)
f_D=vapor pressure deficit modifier (0-1)
f_T=temperature modifier (0-1)
f_{CI}=light competition modifier

This model allows a blend of key sub-models from model 3-PG and a commonly used mensurational equation that avoids the need to directly estimate absorbed photosynthetically active radiation, does not require estimates of carbon allocation, and can be both fitted and used without recursion (that is, with path invariant equations).

8. Existing Climatic Growth Models for New Zealand

8.1 Climatic model for Nelson Forests

This study (Woollons *et al.*, 1997) is concerned with Nelson region *Pinus radiata* forests and the effects of adding climatic variables to height and basal area/ha predictors. The region is complicated in that the forests reside on four distinct soil types that produce sharply contrasting growth-rates. These are colloquially known as:

(a)   Eastern Hill Soils   (EHS)
(b)   High Fertility Granites   (HFG)
(c)   Mapua Clays   (MC)
(d)   Moutere Gravels   (MG)

A top-height model using equation (7.14) was constructed:

$$H = \alpha - \beta((\alpha - H_1)/\beta)^{(T/T_1)^{\gamma}} \tag{8.1}$$

where in (8.1)

   H, H_1 = mean-top-height at ages T and T_1 (T ≥ 0)

Attempts to add climate oriented variables to (8.1) were unsuccessful.

For basal area/ ha, a variant of equation (7.8) gave a model:

$$G = \exp(\ln(G_1)(T_1/T)^{(\beta+\eta\log(N/10))} + \alpha^*(1-(T_1/T)^{(\beta+\eta\log(N/10))})) \tag{8.2}$$

and

$$\alpha^* = (\alpha + \delta.MG.\log(RAIN) + \varepsilon.EHS.\log(RAIN) + \theta.HFG.SOLAR) \tag{8.3}$$

where in (8.2) and (8.3)

   N = stems/ha
   RAIN = mean annual rainfall (mm)
   SOLAR = mean solar radiation (MJ m^{-2} day^{-1})
   $\delta, \varepsilon,$ and θ are dummy variables = 1 for the soil type indicated, = 0 otherwise.
If all three are set to zero, the model collapses to a predictor of basal area/ha for Mapua Clays, devoid of any weather variables.

8.1.1   Discussion

   In this Report it has been emphasised problems will exist with predicting forest growth responses caused through climate change. Only for a few sites is it likely that growth

response will be a simple function of weather alone. More probable will be complex interactions with soil type, topography and annual perturbations of climate and then always subject to Liebig's law.

For this study, each soil type has a unique response to climate including the Mapua clays where no weather variable enhances growth; the forest resides on badly leached clays, very deficient in N, P and B (Ballard, 1977). Although the forest area is small (4300 ha), it provides an example of a forest where nutritional limitations will very probably outweigh any benefit from climate change.

Here, for two soil types (MG and EHS) different coefficients are required to cater for changes in rainfall, but in both cases a curvilinear (logarithmic) relationship is present, so that higher rainfalls progressively produce lesser growth increases. Only for one soil type does solar radiation appear as a significant predictor variable.

The relative paucity of weather predictor variables in this study is not surprising. Utilising projection equations like (8.1) and (8.2) means initial top-height or basal area/ ha are predictor variables.

For climate-growth studies, without modification, projection models will likely mask many environmental/ weather effects. Initial basal area/ ha and top-height are highly successful surrogate measures of site productivity and will account for considerable climatic and local variation. For example, it is well known that mean-top-height is strongly affected by altitude that in turn is closely correlated to temperature (Woollons, 2002), but the presence of initial top-height negates the need for the latter variables. An example of how projection equations can be successfully modified is given in Section 8.3.

8.2 Climatic model for Hawke's Bay Forests

This study (Woollons *et al.*, 1998) is concerned with five forests in the Hawke's Bay region of New Zealand. The forests are

(a)   Esk
(b)   Glengarry
(c)   Gwavas
(d)   Kaweka
(e)   Mohaka

Unlike the Nelson study (above) the five forests can be considered to be on comparable soils, either yellow-brown pumices or yellow -brown earths (Dr's G. M. Will and M. Skinner, *pers. comm.*). The forests are distinguishable however, by altitude, ranging from 300-700 m.

Growth data were available from 155 permanent sample plots. Also available were average temperature, rain and solar radiation statistics.

For mean-top-height, a hybrid growth/ climate model was obtained:

$$H = \exp(\alpha + \theta_1 TEMP + \theta_2 WRAIN + \theta_3 WRAIN^2 + \theta_4 SOLAR + \beta / T^\gamma) \quad (8.4)$$

where in (8.4)

TEMP = average annual temperature (degrees C)
WRAIN = Winter rainfall (June-September) (mm)
SOLAR = mean annual radiation (MJ m^{-2} d^{-1})

Mean-top- diameter (D_{100}), initially was modelled by the Chapman-Richards yield equation. This was successfully augmented to:

$$D_{100} = (\alpha + \theta_{1G} D_G.TEMP + \theta_2 D_{POOL}.TEMP + \theta_3 RAIN_S)(1 - \exp(-\beta T))^{(\gamma + \varsigma / T)} \quad (8.5)$$

where in (8.5)

D_G = a dummy variable = 1 for Gwavas, = 0 otherwise
D_{POOL} = a dummy variable = 1 for the rest of the forests, = 0 otherwise
$RAIN_S$= summer quarterly rainfall (mm) [December, January, February]

8.2.1 Discussion

These results further substantiate the premise that prediction of growth change through climatic influence will be partially confounded or complicated by additional factors. Here, the principal variable is stand altitude, which especially for mean-top-height (and thus volume/ ha) produces several interesting and somewhat complex results.

The signs of the top-height equation (8.4) were all logical. Increased height occurs with higher temperatures but also with higher solar radiation and rainfall. The latter effect is complicated in that around 600 mm of winter rainfall (equivalent to 1600 mm annual precipitation) the effect reaches a maximum and higher values decrease top-height. This result is confounded with a complexity of other factors. Higher rainfall is associated with higher altitudes and thus at lower temperatures and less net solar radiation, and in all probability, increased wind desiccation.

For the top-diameter equation (8.5) the presence of an age of thinning variable confirms results are a little confounded with thinning effects so association with climate variables may be somewhat blurred. Both crown size and root elongation are likely to be under developed with thinning and initially anyway, will be unable to take full advantage of moisture and light (Møller, 1954).

8.3 A National growth model

The models discussed in 8.1 and 8.2 are limited in the sense that they apply only to localised regions in narrow latitudinal ranges. This accounts for the virtual absence of climatic

variables such as annual solar radiation and average temperature-for localised forests these can be regarded as constants.

Working in part with the growth data described in Section (4) above, Dzierzon and Mason, 2006 introduced prototype growth and yield models, potentially operable throughout New Zealand. Two general approaches were explored:

(a)   Stratification of by land environments or soil types
(b)   So-called 'hybrid' growth models

For (a) both LENZ layers (Leathwick *et al.*, 2002, 2003) and Landcare Research New Zealand soil data base (Newsome *et al.*, 2000) were utilised to form two sets of strata. The former utilise a variety of variables (for example mean average temperature over the last 20 years) to form homogeneous groups through a clustering process, while the latter are based on soil types as well as chemical and physical information.

For both (a) and (b) growth models in the form of projection equations are utilised. It was noted in 8.1.1 that projection models are usually less successful at modelling climatic predictors.

They can however be modified, a technique first utilised by Snowdon *et al.* (1998) and Snowdon (2001). Consider the projection model:

$$G = \exp(\ln(G_1)(T_1/T)^\beta + \alpha(1-(T_1/T)^\beta)) \qquad (8.6)$$

where in (8.6)

G_1, G = initial and final basal area/ ha at ages T_1 and T (T > T_1)

However, if the age variables are replaced by accumulative rainfall (Snowdon, 2001) or solar radiation (Mason, 2007), where the climate estimates are obtained from appropriate climatic layers, a workable model emerges. From the PSP records, and for a specific plot, the actual month(s) and year(s) when two successive growth measurements were acquired can be matched by the rainfall or solar estimates. For a sequence of measures for any plot, monthly rainfall/ solar estimates can be expressed in an accumulative form, and equation (8.14) for example would become:

$$G = \exp(\ln(G_1)(SL_1/SL)^\beta + \alpha(1-(SL_1/SL)^\beta)) \qquad (8.7)$$

where in (8.7)

SL_i, SL = the accumulative incoming solar radiation received up to when the plots was measured at ages T_1, T (T > T_1)

Dzierzon and Mason further refined equation (8.7) by allowing the parameters (α or β) to be adjusted by further climate variables. For example, available soil moisture is fundamental to tree growth (Landsberg and Waring, 1997) and one moisture index is maximum available soil water (ASW_{max}) (Webb and Wilson, 1995). ASW_{max} is essentially a measure of total available water to a depth of 0.9 m., and is available from the Landcare climatic database. However, it is likely that this variable will have the same limitations as PAW, discussed in section 3.4.

Model (8.7) was augmented to:

$$G = \exp(\ln(G_1)(SL_1 / SL)^{(\beta + \gamma ASW_{max})} + (1 - (SL_1 / SL)^{(\beta + \gamma ASW_{max})})) \quad (8.8)$$

8.3.1 <u>Results for the national growth model</u>

Compared to a pooled model, stratification through either the LENZ or Landcare soil classes gave significant increases in precision (up to 29 %) for equations predicting either top-height or basal area/ha. Overall, stratification through the LENZ layers was superior to soil classification.

Hybrid modelling also gave appreciable gains in precision (14 %) although gains were largely limited to basal area/ha, mean-top-height giving 8% improvement. The usage of both solar radiation and available water as predictor variables as opposed to <u>either</u> solar <u>or</u> water was only marginally superior.

The climatic equations were compared to conventional regional growth models (for example, equation 8.6) for the Canterbury and Central North Island regions. Sharply different results emerged. Whereas the Canterbury region was well modelled (both for top-height and basal area/ha) especially by the hybrid models, the Central North Island performed badly, with both the stratified and hybrid approaches having error mean squares up to 66 % higher than conventional models. It is suggested that the lack of an altitude variable (either explicitly or implicitly though temperature) may account for this.

9. New Climatic Models for New Zealand

9.1 A simple climate model for the North Island of New Zealand

This study was originally intended to explore what environmental and topographical predicted mean-top-height. Here it is very briefly reviewed then expanded, to provide volume/ha estimates through changing weather conditions.

Most of the data were first collected by Hunter and Gibson, 1984. The authors used a combination of climate, soil, and nutrient variables to build a multiple regression model. Later, the data were augmented by updated and more extensive climate data.

Woollons *et al.*, 2002 constructed a mean-top-height regression model operable for the majority of North Island forests. Beginning with the log-reciprocal yield equation (7.1) this was subsequently expanded to:

$$H = \exp(\beta_0 + \beta_1/T + \beta_2 I.ALT + \beta_3 RAIN + \beta_4 WIND + \beta_5 \log(ADAH + 1))$$ (9.1)

where in (9.1)

T	= stand age (years)
ALT	= stand altitude (m)
RAIN	= mean annual rainfall
WIND	= average wind speed (km/hour)
ADAH	= average depth of the A horizon
I	= a dummy variable, I = 0 for Raw or Sandy Recent soils
	= 1 otherwise

The error mean square of 9.1 was 9.33, an increase in precision of 45% relative to model (7.1). All the signs of the coefficients are logical with bigger height growth occurring at lower altitudes, in the presence of larger rainfall, less wind and a longer A-horizon profile.

9.1.2 A new net basal area model

For this project, the data was re-visited with view to building a simple growth system to estimate volume/ha growth due to climatic change. To achieve this, it is desirable to obtain an equation to predict net basal area growth.

A log-reciprocal projection model (7.8) gives an excellent summary of the growth data, but predictably takes out the effects of any climatic variables. As such, a yield model was substituted, but was allowed to utilise a stocking term as a predictor variable. Normally, this would cause complications in that the stocking values would have to *a priori* known. Here, with intent on point (age) estimates and estimating change in growth through climatic change, it is envisaged that stocking at a given age can be considered a constant for most forests, or can be reasonably estimated, without biasing results.

A model:

$$G = \exp\left(\alpha + \frac{\beta_1}{T^{0.5}} + \beta_2 \ln(N)\right) \qquad (9.2)$$

where in (9.2)

N = stems/ ha at age T

gives a reasonable fit of the data, with individual point predictions of basal area likely to be within ± 8.5 m^2/ ha.

Attempts were made to augment (9.2) with climatic predictors. After considerable modelling, an equation emerged:

$$G = \exp\left(a + \frac{\beta}{T^{0.5}} + \beta_1 \ln(RAIN) + \beta_2 \ln(N) + \beta_3 ADAH\right) \qquad (9.3)$$

All coefficients are significantly different from zero, as evaluated by approximate 99% confidence intervals. No other climatic or topographic variable came near to significance.

The coefficients are logical with larger basal area expected with more stems/ ha, rainfall and depth of the A-horizon. A point specific estimate of basal area is likely within ± 7.4 m^2/ha, a 15% improvement in precision., relative to (9.2).

Figure 9.1 gives a histogram of the residuals from (13) for the major soil types. Over all, and among soils, the model is reasonably unbiased.

Model (9.3) is more flexible than probably seen at first sight. For example, it might be concluded that since there are no altitude or temperature terms, the model will illogically give substantial basal area/ ha estimates at very high elevations. This will not be so, since stocking estimates will inevitably become significantly lower, a consequence of exposure while the curvilinear function of rainfall will limit the latter's influence.
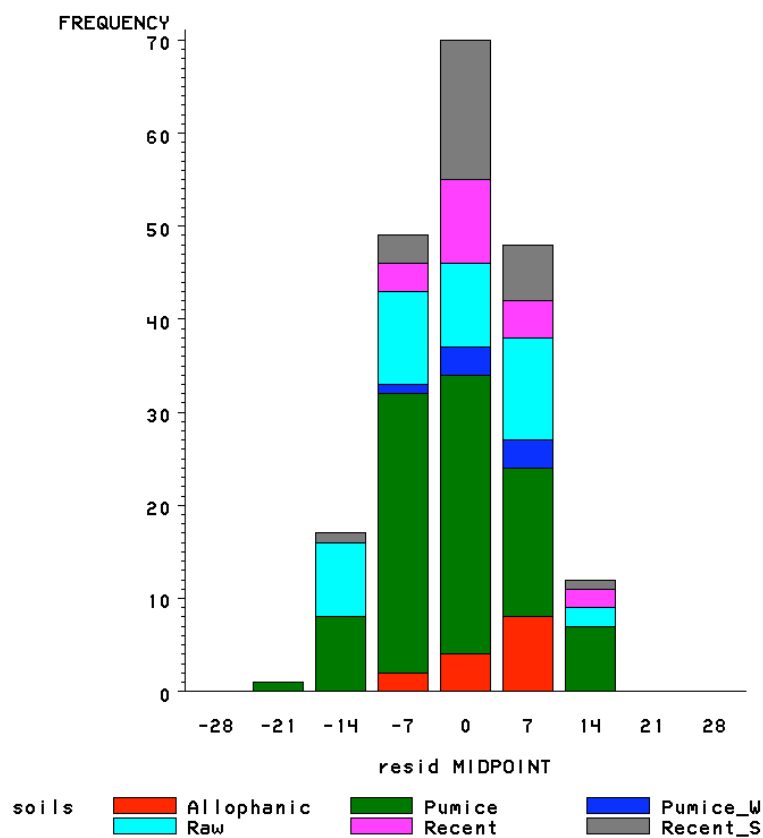
Figure 9.1 Histogram of residuals from model (9.3)

9.1.3 Model for volume/ ha

The product of net basal area/ ha and mean-top-height is closely related to volume/ha so it is straight-forward to build a reliable predictor equation.

A straight-line model:

$$V = 26.23799 + 0.317036GH \tag{9.4}$$

where in (8.13)

V = net volume/ha (m^3)

fits the data very well; the R^2 value = 0.98

9.1.4 Predictions of growth change

Table 9.1 summarises the relevant climate and topographic data for the major soil types.

Soil Type	Age (y)	Alt (m)	Rain (mm)	A-Horizon (cm)	Wind km/h	Stocking (stems/ ha)
Raw	23	31	1183	1.3	11	545
	14-40	2-102	902-1570	0-5	8-13	158-2079
Recent (Sandy)	28	42	1255	5.3	11	367
	16-40	15-83	903-1610	1-20	8-13	128-642
Brown	22	257	1666	13.6	12	515
	10-31	30-576	918-1940	3-36	8-14	208-1254
Pumice	21	386	1552	15.2	8	446
	13-38	55-652	1230-1900	7-36	6-11	89-1535

Table 9.1: Summary of climatic data by major soil type for the Hunter data.

From these data and utilisation of models (9.1), (9.2) and (9.3) it is possible, albeit necessarily making several assumptions, to estimate the order of unit area volume that may be forthcoming from favourable climatic change.

One very simplistic example is given here, for the Central North Island Pumice soils, where the majority of other major limiting factors are probably minimal. The region receives an adequate rainfall and does not have major nutrition deficiencies (Will and Stone, 1967; Will, 1985).

From Table 9.1, assume currently:

    Rainfall = 1552 mm
    Altitude = 286 m
    Ave. wind-speed = 8 km/ h
    Ave. A-horizon depth = 15 cm

For age = 30 years

and utilising equation (9.1), the predicted mean-top-height

    = 38.4 m

Assume a stocking of 350 stems/ha is present, then from equation (9.2), the predicted basal area/ ha = 56.4 m^2/ha.

From equation (9.3) these values are equivalent to a volume of 713 m^3/ha.

Now assume that in the future, the annual rainfall increases to 1652 mm and average the A-horizon depth increases to 16 cm.

Using the same equations, the estimated volume/ha = 740 m^3/ha, so the estimated response to the new climate/soil status = 27 m^3/ha, a 4% response.

On silvicultural grounds this will probably be an over estimate. Equation (9.3) predicts a total stem, fully stocked volume. Allowing for breakage, waste, actual (rather than nominal) stocking, and net area, then a common realisation factor is 0.85, to a better estimate of the climate response is 23 m^3/ha.

9.2: A new Regional hybrid Model involving potentially usable light

Given the constraints on soil water balance modelling, it is deemed best to illustrate potentially useable light sum modelling using a region where water is generally plentiful and where the forestry sector has a large area of plantations. The Central North Island region, in and around Kaingaroa, generally has plentiful rainfall all year around, and productivity is strongly related to elevation (Mason 1992; Mason and Whyte, 1997; Mason, 2001), an effect attributed to temperature.

The models created by Methol (2001) for radiata pine in the Central North Island were adapted for use with a potentially useable light sum approach. Methol used difference equations to model mean top height, basal area per hectare, and stems per hectare using time-based difference equations.

A Schumacher form was best for basal area, and Richards-type model fitted best for mean top height projections. Methol found that using linear models of altitude as the asymptotic parameters for both models, and also for the shape parameter of the mean top height model. The two equations are:

Basal area/ ha

$$G = \exp(\ln(G_1)(T_1/T)^{\beta} + \alpha(1 - (T_1/T)^{\beta}))$$
(9.5)

and

Height

$$H = \alpha \left(\frac{H_1}{\alpha}\right)^{\frac{\ln(1 - e^{(-\beta T)})}{\ln(1 - e^{(-\beta T_1)})}}$$
(9.6)

For the height model both the a and b parameters were linear functions of altitude, while for the basal area model only the a parameter was a function of altitude.

During the study described here, these models were converted to a hybrid approach by substituting potentially useable light sums for time.

Radiation measurements from the Rotorua Airport were used to calculate radiation in each month since time of planting for each PSP in the dataset. The mean daily temperature in each month was calculated using an offset technique. Monthly measurements at Rotorua Airport were assembled. Then the corresponding temperature at each PSP location was

estimated by using the difference between mean daily maximum and minimum temperatures at the airport and those at the PSP using equations developed by Norton, 1985.

Norton's equations employ latitude, altitude, and distance from the sea to estimate long-run temperature normals. Within the region, altitude was by far the most influential variable affecting temperature, according to Norton's equations.

A water balance model was created for each plot that was identical to that used in 3-PG (Landsberg and Waring, 1997). A leaf area index model was required for the water balance, and based on LAI measurements in Canterbury (Pinjuv *et al.* 2006) a simple exponential model was assumed with an asymptote of 6.5 that was reached by approximately age 15 (details are available on request). The soil water modifier used for light sums was also identical to that used in the 3-PG model. Monthly weather and LAI estimates were assembled as related tables in a database, and then a water balance model was run over the first four years of measurements in each plot, using a monthly time step.   Maximum stomatal conductance was assumed to be 0.02 m/sec and maximum boundary layer conductance was assumed to be 0.2 m/sec.

Vapour pressure deficit (VPD) was estimated from mean daily maximum and minimum temperatures by assuming that vapour pressure deficit was 0.5 times the saturated vapour pressure at the maximum temperature minus saturated vapour pressure at the minimum temperature.

A VPD modifier was used that is identical to that used in the current version of the 3-PG model. It was represented as:

$$f_D = \exp(-0.05 VPD)$$

(9.7)

where in 9.7

 VPD=vapour pressure deficit.

This modifier was also used to calculate stomatal conductance from maximum stomatal conductance in the water balance model.

A temperature modifier, also identical to that used in the 3-PG model was based on the minimum, optimum and maximum temperatures for photosynthesis as:

$$f_T(T_a) = \left(\frac{T_a - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T_a}{T_{max} - T_{opt}}\right)^{(T_{max} - T_{opt})/(T_{opt} - T_{min})}$$

(9.8)

where in (9.8)

$f_T = 0$ if $T_a \leq T_{min}$ or $T_{max} \leq T_a$, and T_{min}, T_{opt} and T_{max} were the minimum, optimum and maximum temperatures for net photosynthetic production. T_a was the mean temperature for each month. The minimum, optimum, and maximum temperatures for photosynthesis were assumed to be 6, 22 and 35 degrees respectively (Walcroft *et al.* 1997).

The radiation sums for each month were multiplied by the temperature modifier, and sums from time of planting to the beginning and end of each interval in the dataset were created. These light sums were then substituted for time in the sigmoidal equations used by Methol. The models therefore became:

Basal area/ha

$$G = e^{\ln(G_1)\left(\frac{R_1}{R}\right)^{\gamma} + \alpha\left(1 - \frac{R_1}{R}\right)^{\gamma}}$$

(9.9)

where in (9.9)

R_1 and R_2 = radiation sum from time of planting to the beginning and end of the growth interval respectively. In this case the radiation sums were modified by local mean daily temperature in each month using equation 9.8. The radiation sum was therefore:

$$R = \sum_{t=1}^{T} R_t f_T$$

(9.10)

where in (9.10)

R_t = the total radiation sum for month t
f_t = the temperature modifier (equation 9.8) for month t.

Daily temperature was defined as:

mean daily maximum x 0.7575 + mean daily minimum temperature x 0.2425.

These latter factors assumed a sinusoidal variation in temperature between the two extremes, with the maximum occurring at 3 pm each day. The a parameter was fitted as a linear function of mean annual temperature modified radiation since time of planting. Compared to a simple time-based model using a linear function of elevation for the asymptote, the root mean square error was reduced from 3.76 to 3.37.

A full potentially useable light model was attempted (Mason *et al.* 2007), with radiation modifiers for vapour pressure deficit and soil water. The asymptote was a linear function of

mean annual potentially useable light sum since time of planting. The radiation sum was therefore:

$$R = \sum_{t=1}^{T} R_t \min\left[f_\theta f_D\right]f_T \qquad (9.11)$$

where in (9.11)

R_t = s the total radiation sum for month t
f_θ = the soil water balance modifier
f_D = the vapour pressure deficit modifier (equation 9.7)
f_t = the temperature modifier (equation 9.8) for month t.

This slightly increased the root mean square error to 3.41. Two sources of error may contribute to the root mean square error being a bit larger than the simpler temperature modified radiation model. Firstly, maximum and minimum soil water are known to be wrong within the fundamental data layer, as described previously, and secondly, we had to assume a leaf area index model in order to run the water balance model.

<u>Height</u>

$$H = \alpha \left(\frac{H_1}{\alpha}\right)^{\frac{\ln(1-e^{(-\beta R)})}{\ln(1-e^{(-\beta R_1)})}} \qquad (9.12)$$

For this model both the asymptote and shape parameters were set as linear functions of average modified radiation since time of planting, just as both had been linear functions of elevation for the time-based model. Results for the mean top height model were similar to those of the basal area model. The root mean square error was decreased from 0.997 using time to 0.990 by using a models based on radiation modified by daytime temperature. Using a full potentially useable modified light model, with temperature, vapour pressure deficit and soil water balance radiation use modifiers, led to a decrease in the root mean square error to 0.982.

It was decided that, as temperature was the main variable projected to change in future, temperature modified light sum models were the most appropriate models to use for projecting likely impacts on plantation growth.

10. NIWA'S Estimates of Changes in Future Climate Within New Zealand

NIWA recently published through the Ministry of Environment (MOE) details and predictions of changes in climate with New Zealand (Ministry for the Environment, 2008). The documentation is extensive (167 pp.) and only a very brief summary is given here, focussing on elements that are likely to affect forest plantations.

A key table is given on page 14 (MOE Table 2.1), which summaries the main features of New Zealand climate change projections. Crucial points are:

(1)   An increase in mean temperature, equating to 0.9^{o} C by 2040 and 2.1^{o} C by 2090.

(2)   Mean rainfall, to vary around the country. Increases in Tasman, West Coast, Otago, and Southland. Decreases in Northland, Auckland, Gisborne, and Hawke's Bay. No significant changes elsewhere.

(3)   Increases in annual average westerly component of wind-flow across New Zealand. Estimated to be a 10 % increase in strong   winds by 2090.

It is worth noting that neither solar radiation or vapour pressure deficit are cited as major changes.

11. Prediction of Future Growth Response Utilising Hybrid Growth Equations (9.2) and NIWA Forecasts of Climate Change

11.1 Method

The hybrid models described in Section 9.2 are utilised here to predict likely changes in forest yield in the Central North Island assuming NIWA estimates of climate change.

In order to simulate likely crop responses to changing climate in the Central North Island region, two contrasting sites were selected. Productivity is strongly influenced by altitude in this region (Mason, 1992), and so sites at altitudes of 400 and 700 m.a.s.l. were chosen. The initial growth model (Mason, 2001) was used to derive starting values for these sites, as it is sensitive to altitude, and has been shown to join smoothly with existing growth and yield models for the Kaingaroa vicinity (Mason, 1997). For 2040 the same starting values were employed.

Using the same starting values for each year of simulation might provide conservative estimates of change, but we are mindful of two major caveats:

(1)   The models do not yet take into account any deleterious effects of wind.

(2)   Changes in regional temperature may not be uniformly allocated across altitudes (that is, at higher altitudes, predicted increases in temperature may be less than a general average figure). NIWA advice is that detailed studies have been limited to surface fields. (Dr. Andrew Tait, *pers. comm.*)

The sites and starting values are shown in Table 11.1.

Elevation (m.a.s.l.)	Mean ht (m)	Basal area (m^2/ha)	Stocking stems/ha	MTH (m)
400	6.72	9.11	814	8
700	4.1	3.92	720	4.9

Table 11.1: Site characteristics and starting values for simulations

For each site a daytime temperature modified light sum was calculated for the years 1985 to 1995, and for the same years but adding 1°C to summer and autumn temperatures, 0.9°C to winter temperatures, and 0.8°C to spring temperatures, as specified in the NIWA climate projections (Ministry for the Environment, 2008) for the Bay of Plenty region.

These modified light sums were then replicated to reach age 30 for the simulation at each site. The regimes specified for each site was planting 1000 stems/ha and then thinning down to 300 stems/ha at a mean top height 10 m.

Estimated gains in productivity are shown in Figures 11.1, 11.2 and 11.3.
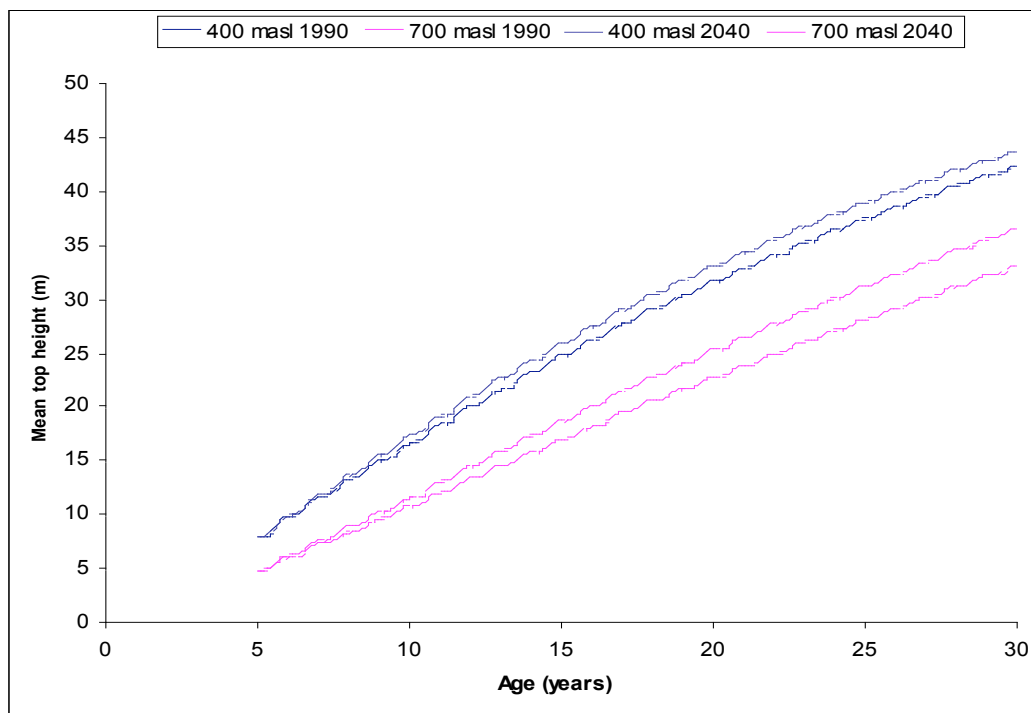

Figure 11.1: Mean top height development at each site in each epoch
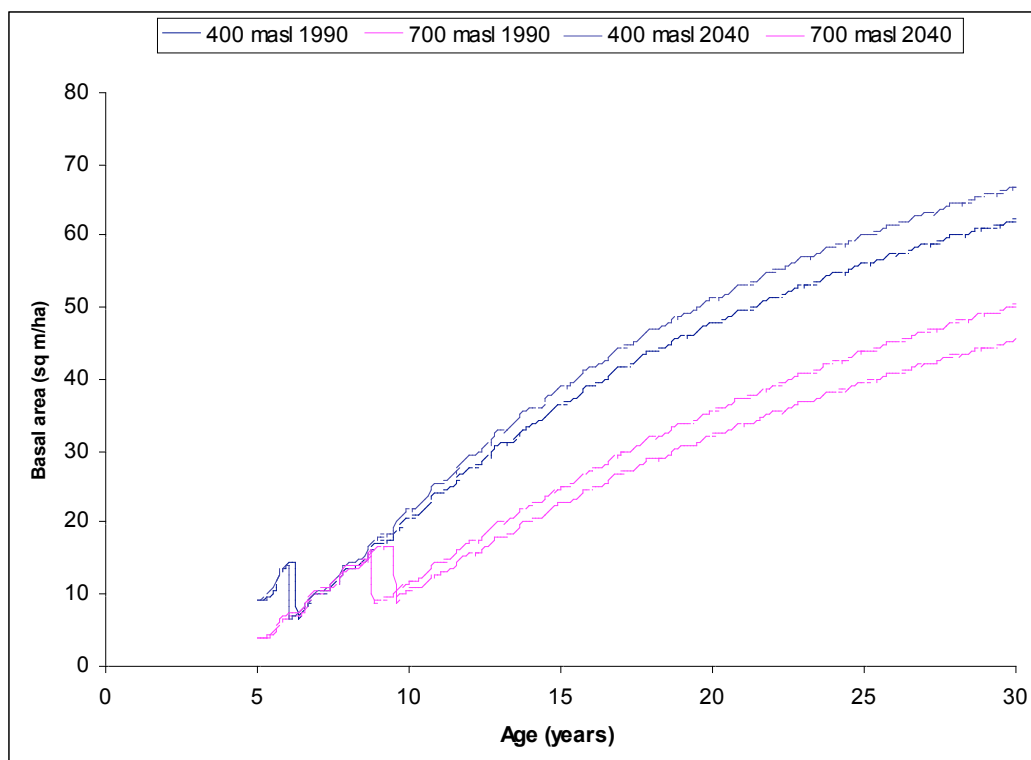

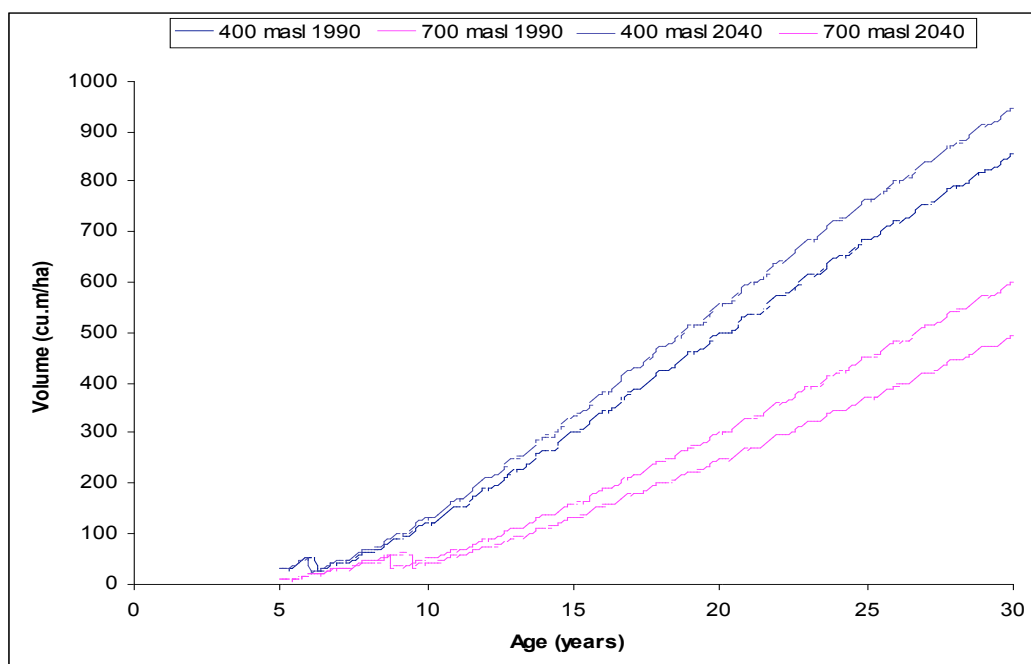Figure 11.2: Basal area/ha development at each site and epoch

Figure 11.3: Stem Volume/ha at each site and epoch

The wavy plots depict the influences of monthly radiation and temperature variation on growth within each year.

The impact of projected changes in temperature on the simulation was greater for the higher elevation site, because at lower elevations the optimum temperature for photosynthesis of radiata pine is sometimes exceeded and therefore increasing temperatures during summer occasionally reduced the potential for light to be used for photosynthesis.

Estimates of enhanced growth through climate change in the order of 70-100 m^3/ha in a 30 year rotation are shown, but these must be considered in relation to the caveats listed above.

12. Blueprint for Developing Models of Climate Change on Forest Growth

12.1 On-going program of work

From this report, we see clear priorities for future work.

The research described in this report was conducted in a limited time frame, and further work is required in order to provide more reliable estimates of the impacts of climate change on forest growth and yield.

1   The existing works are confined to the North Island, with emphasis on the Central North Island region. It is proposed to extend the studies to other regions, including the South Island.

2   In regions where rainfall changes are projected, a soil water balance model will be required, and adjustments will have to be made to current database estimates of plant available water (PAW) in order for these models to be realistic. This requires further assessment of PAW in soils under forest cover across New Zealand. It is hoped that some generalizations may be made from a sufficiently large number of comparisons so that adjustments for other soil- types might be estimated. Approximately 150 comparisons would be enough to indicate whether or not such an approach is feasible.

3   The climate data estimates obtained from NIWA are sufficiently different from those estimated by Landcare Research that we need to rationalize the two and obtain good daily estimates for each PSP site before proceeding to a multi-region model. Given a sufficient improvement in weather estimates for points in the landscape, the Central North Island region study should be redone as well.

Mortality was not included in the study reported here, and it is likely that it will be affected by changes in climate. Malte Coulmann will make this subject of his MForSc thesis, using the Canterbury region as a template.

4   There is a case for further development of traditional management yield models in the major forest growing areas (for example, CNI), stratified by altitude bands. While these will not mimic mechanistic processes they will be invaluable for checking the magnitude of productivity changes as assessed by hybrid systems.

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