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GROWTH VARIATION AMONG SITES - A MODELLING PERSPECTIVE

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EXECUTIVE SUMMARY

The effect of environmental variables on the growth of radiata pine is reviewed.

Approaches to modelling growth variation among sites is discussed. It is concluded that the development of regional growth models is a sound approach.

Research projects for the Stand Growth Modelling Co-operative are proposed.

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INTRODUCTION

The project "Growth Variation Among Sites" was proposed in the Stand Growth Modelling Co-operative 3-year Research Programme 1990-1993. The objective was to establish a research programme which:

> examined the causes of the different growth patterns between regions and sites
>
> attempted to establish the relationship between growth and environmental factors in New Zealand.

Tree growth is the result of a series of complex physiological processes many of which are still poorly understood. Stand growth is the product of tree growth and the interaction between trees. Understanding the observed variation in stand growth from a physiological basis is therefore a very long-term project and is considered to be beyond the scope of this project. Research will concentrate on investigating the relationships between growth and "easily measured" environmental variables (i.e. variables which have the potential to be measured/estimated for all permanent sample plots if they prove to be of use in modelling growth). For the purpose of this project "environmental variables" are interpreted as being climatic variables, properties of the soil, properties of the site (e.g. slope, aspect) which are surrogates for other variables, and foliar nutrient concentrations which are an indication of the soil's ability to provide nutrients. A number of these environmental variables are however altered by stand management.

OBJECTIVE

The objective of the stand growth modelling co-operative project "growth variation among sites" is therefore defined as:

> understanding the relationship between radiata pine growth and easily measured environmental variables

with the long-term objective being to improve the current growth models by:

> revision of the current growth modelling regions
> inclusion of environmental variables in growth models
> development of indices of site quality that are an improvement on site index

CONTENTS

This report contains:

> Literature review of variation in radiata pine growth with environmental variables
> Proposals for research under this project

LITERATURE REVIEW

INFLUENCE OF ENVIRONMENTAL FACTORS ON THE GROWTH OF RADIATA PINE

There have been several reviews of the influence of environment on radiata pine (e.g. Raupach, 1967; Gandullo et al, 1974; Lavery, 1986; Grey, 1989).

GROWTH VARIATION WITH CLIMATIC VARIABLES

RAINFALL

Several studies have recommended optimum annual rainfall ranges for growing radiata pine. For example, Hinds and Reid (1957) suggest that 900 -1800 mm is optimum for radiata pine in New Zealand. This is similar to the optimum range of 1000-1940 mm suggested for Spanish conditions (Gandullo et al, 1974). In South Africa commercial planting is not recommended below an annual rainfall of 650 mm (Grey and Taylor, 1983).

Height growth appears to be affected by annual rainfall. For example, site index was found to increase with the log of mean annual rainfall (Hunter and Gibson, 1984); and annual rainfall was found to influence the shape of the curve of stand mean internode length versus height of internode within the tree (Grace and Carson, 1993).

Jackson and Gifford (1974) found that annual rainfall interacted with effective soil depth to affect periodic stem volume increment . For a given effective soil depth, there appears to be optimum annual rainfall for volume production. This optimum increases with effective soil depth. With an effective soil depth of 400 cm, the relationship appears to be linear.

The seasonal distribution of rainfall is also important. Radiata pine does not grow well where summer drought or soil moisture deficit is too severe (Lavery, 1986). Jackson and Gifford (1974) indicate that rainfall in June, July and November to February are positively correlated with volume increment. An experiment (Jackson et al, 1976) indicated that summer/autumn drought (access to water restricted from December to May) reduced both basal area growth and the secondary peak height increment which occurred in autumn in the non-drought treatments. A winter/spring drought (access to water restricted from June to November) had little effect on basal area increment but reduced height growth in November (the month of maximum height increment in the non-drought treatments).

Rainfall influences water availability. The effect of water availability on growth is discussed later.

TEMPERATURE

Several studies have quoted optimum mean annual temperature for radiata pine: 10.3^0 - 13.9^0C (Gandullo et al ,1974), 12^0C (Hunter and Gibson, 1984), 12^0 - 14^0 C (Booth and McMurtrie, 1988) and at least 15^0C (Hollinger, 1990). However the last result should be treated with caution (Grace et al, 1991). The model developed by Hunter and Gibson (1984) predicts site index will decrease linearly with the absolute difference between mean annual temperature and 12° C.

That there is an optimum temperature for radiata pine seems realistic as both photosynthesis and respiration rates have been shown to depend on temperature. There is a range of temperatures over which photosynthesis rate is optimum (e.g. Jarvis and Sandford, 1986) while respiration rates increase with increasing temperature (e.g. Beneke, 1984).

Radiata pine is susceptible to leader damage at extreme low temperatures. The level of frost tolerance varies seasonally. In summer radiata pine will not tolerate frosts below -6°C while in winter it can tolerate frosts as low as -14°C (Menzies and Chavasse, 1982).

In Spain, mean temperature of coldest month was found to be negatively correlated with "quality class" (lower quality class number implies better growth) (Gandullo et al, 1974). However they indicate that there is an optimum range for the mean temperature of the coldest month, 4.2° C to 8.1° C, based on the distribution of a representative sample of plots.

WIND

A study of daily radial growth of radiata pine in South Africa appears to indicate that diameter growth is reduced when wind velocities exceed 18 knots in summer (van Laar, 1967). However, the trend was not significant.

LIGHT

Photosynthetically active solar radiant energy (PAR) is necessary for photosynthesis and hence tree growth. The rate of net photosynthesis increases to an asymptote with increasing PAR (see e.g. Grace et al, 1987a). Grace et al (1987b) showed that the annual above ground productivity of radiata pine at Puruki (near Rotorua) is positively correlated with intercepted PAR. From studies in Australia (Raison and Myers, 1992) the slope of the relationship between above-ground net primary production and intercepted PAR varies with the level of water and nutrient stress experienced by the stand. Raison and Myers (1992) found that the relationship:

$$NPP = (2.285 + (1.633 + 0.915\ F)\ W)\ PAR$$

where:

NPP is the above-ground net primary production (t C ha^{-1} yr^{-1})
PAR is intercepted PAR (GJ m^{-2} yr^{-1})
W is annual stand water use (m yr^{-1}) (Myers and Talsma, 1992)
F = 0 (absence), =1 (presence) of N fertilisation

explained 94% of the annual variation in net primary production.

Demetriades-Shah et al (1992) suggest that there will always be a good correlation between interception and growth of a plant, even when illumination is not a limiting factor. However for radiata pine, a measure of intercepted light could be useful for predicting the differences in growth for stands which do not fully occupy the site or that have different crown structures, for example stands with different levels of genetic improvement. The use of crown length to predict growth in the model "EARLY" (West et al, 1982) is fulfilling this role for thinned and pruned stands.

Will (1962) considers that daylength, rather than soil or air temperature limits the growth of radiata pine in Kaingaroa Forest during the winter. The model of Grace et al (1987a) supports this conclusion to some extent in that it indicates reduced photosynthesis during winter due to differences in solar radiation. However, the differences appear to be due to both distribution of solar radiation within the stand and daylength.

GROWTH VARIATION WITH SOIL VARIABLES

GROWTH VARIATION WITH SOIL PHYSICAL CHARACTERISTICS

In terms of soil texture, tree growth is better on clay loams than on either heavy clays or sandy loams (Spurr and Barnes, 1980) due to heavy clays being aeration deficient and sandy soils being moisture deficient.
In Gippsland (Victoria, Australia), Turvey (1983) showed that the shape of the curve of total volume production with age varied with soil type.

In a later study in the Lithgow district (New South Wales, Australia) covering seven geological groups, Turvey et al (1986) found that soil depth was positively correlated with basal area (0.76) and dominant height (0.82) while percent sand was negatively correlated with these variables (-0.42 and -0.44 respectively). No soil chemical variables were significantly correlated with basal area. However dominant height was significantly correlated with total P (0.27), exchangeable Mg (0.28) and exchangeable K (0.38).

In South East Australia, the height of radiata pine (adjusted to age 30 years) at first increased rapidly with increasing soil depth (either total depth or depth to clay for very deep profiles) and then decreased (Raupach, 1967). The optimum depth was about 75 cm.

As mentioned earlier, volume production of radiata pine in New Zealand generally increased with effective soil depth (Jackson and Gifford, 1974).

Depth of the A horizon also appears to be important. In New Zealand site index has been predicted to increase with log(1+ depth A horizon) (Hunter and Gibson, 1984). In Chile, site index increases to a maximum with increasing depth of the A horizon and then decreases (Schlatter and Gerding, 1984). This appears to be related to the amount of clay and coarse sand in the A horizon.

Root penetration and hence tree growth can be influenced by the bulk density or degree of compaction of the soil. Site index has been found to decrease with increasing bulk density (Schlatter and Gerding, 1984); and with a function of resistance to penetration (Hunter and Gibson, 1984).

GROWTH VARIATION WITH NUTRITION

Hunter et al (1991) produced an atlas of radiata pine nutrition in New Zealand which summarises the observable effects of deficiencies in nitrogen, phosphorus, potassium, magnesium, and boron.

Nutrient status of both A horizon and sub-soil (to 60 cm) was found to influence site index of radiata pine in New Zealand (Hunter and Gibson, 1984). On the Tsitsikamma plateau in South Africa, an area of relatively homogeneous macroclimate, Louw (1991) found that the nutrients in both A and B horizon were important, with site index being predicted to increase linearly with exchangeable aluminium in A horizon and bray 2 phosphate in B horizon, and to decrease linearly with the ratio: total nitrogen/organic phoshate in the B horizon. Physical soil characteristics also influenced site index. In Chile, it was found that site index increased to an asymptote with total carbon in the A horizon and with total nitrogen in the A horizon (Schlatter and Gerding, 1984).

Near Canberra, Australia, Raison and Myers (1992) found a correlation of 0.96 between above-ground net primary production and foliar N content (kg ha^{-1}).

In terms of stem growth, Hunter et al (1987) found that 87.2% of the variation in annual volume increment in a nitrogen and phosphorus trial over five sites could be explained by the N content in the needles (kg N ha^{-1}). A linear regression with canopy weight (kg ha^{-1}), foliar N (%), N fertiliser (kg ha^{-1}) and P fertiliser (kg ha^{-1}) explained 92.2% of the variation.

The amount of phosphorus in the foliage has been used to predict the growth of radiata pine on clay soils in the in the Auckland region (Shula, 1987). Shula (1987) modelled the changes in growth by predicting the time required to achieve a unit of growth as a function of foliar phosphorus concentration.

For two trials on intensively podzolised soils (in Waipoua Forest and Utakura Plantation), potassium fertilisation in addition to nitrogen and phosphorus fertilisation increased basal area growth by 29% and 55% respectively and height growth by 200% and 73% respectively between the ages of 5 and 7 years . The large increase in height at Waipoua Forest was influenced by reduced height growth of N and P fertilisation compared with the control. The increase in height growth with NPK over the control was only 36% (Hunter, 1984). Within New Zealand, potassium nutrition in radiata pine is generally satisfactory. Hunter and Gibson (1984) indicate potassium is important for predicting site index in Chile, however no mention is made in Schlatter and Gerding (1984).

Severely magnesium-deficient trees are stunted. Pruning and spring drought appear to increase magnesium deficiency (Will, 1966). Height growth, after pruning, on a magnesium deficient site was less than expected (Hunter et al 1991). Height and diameter growth can be improved by the addition of magnesium fertiliser (Hunter et al, 1986).

Boron deficiency appears to occur on coarse-textured soils in a low-rainfall environment. The symptoms are die-back of terminal buds which causes stem malformation (Hunter et al, 1990a) and irregulaties of crown form (Stone and Will, 1965). Die-back leads to a reduction in height growth (Stone and Will, 1965).

Low foliar copper concentration causes stem and branch twisting and has been observed on some recent wind-blown sands and on some peat-covered podzols in New Zealand. The addition of nitrogen and phosphorus fertilizer can lead to copper deficiency on soils with marginal amounts of copper (Hunter et al, 1990b). A study in South Australia (Raupach and Clarke, 1978), comparing growth with foliar nutrient contents, indicated low levels of copper produced trees with less height growth and greater diameter growth than normal.

Raupach and Clarke (1978) also found that low levels of manganese and chloride in the foliage produced shorter and fatter trees than normal.

Zinc deficiency has been observed in one stand on a podzolised soil in New Zealand (Will, 1990).

GROWTH VARIATION WITH WATER AVAILABILITY

Water availability is often the most important factor affecting stem growth by regulating the period during which stem growth is possible (Benson et al, 1992). In the absence of adequate water availability, trees are unable to utilise available nutrients. Nutrient availability becomes important when water availability is adequate (Benson et al, 1992). Myers (1988) showed a strong curvilinear relationship ($r^2 = 0.91$) between stand basal area increment ($m^2\ ha^{-1}yr^{-1}$) and a water stress integral (MPa days) with basal area increment decreasing with increasing water stress. The water stress integral involves measuring pre-dawn water potential. However it is not considered practical to routinely measure pre-dawn water potential within permanent sample plots.

GROWTH VARIATION WITH TOPOGRAPHY

Topography influences growth through local modification of environmental variables, in particular, light, moisture and temperature regimes (Lavery, 1986). However topographical variables are often easier to measure than some environmental variables. For example precise equations for predicting black oak site quality in S.E. Ohio included several soil features which were difficult to measure in the field. Less precise equations based only on topographical features were still acceptable and were recommended for use because they were easy to apply in the field (Carmean, 1975). However topography is unlikely to be sufficient to explain differences in growth over an area covering a range of climatic and soil regimes.

Two examples where topography has been used to explain differences in radiata pine growth are given below.

In an area with only relatively minor changes in geology, Ballard (1971) found significant correlations between predominant mean height of radiata pine at age 40 years and slope, aspect and an assessment of soil drainage. However, soil drainage was considered to be a function of productivity rather than the other way round because the application of superphosphate to poorly drained plots led to a considerable improvement in the drainage characteristics of the plots.

Mountfort (1979) showed that site index of radiata pine on pumice soils in the Central North Island decreased with increasing altitude.

MODELLING GROWTH VARIATION AMONG SITES

The above review clearly indicates that environmental variables influence the growth of radiata pine. However the knowledge is too fragmented to state with confidence what is causing the differences in growth between sites and regions. We need to set in place a research programme that will answer that question and will enable us to develop improved growth models.

There have been numerous attempts to use environmental variables for predicting growth, however no approach has proved to be so successful that it has become a "standard approach".

One of the common analyses is to attempt to predict site index from environmental variables. Such studies have often failed to demonstrate significant relationships between logical soil properties and stand variables (Gale et al, 1991) due to three main reasons: multicollinearity between soil variables, failure to incorporate soil-property interactions and small sampling range for soil variables. The importance of sample area is emphasised by Carmean (1975) who suggests that the best compromise is to have a study area with well defined geological, soil, topographical and climatic boundaries in preference to very large area (where sampling is a problem) or small area (where applicability is a problem).

Sample area has been raised by a number of other authors in this context. For example, Turvey (1983) suggests that the soil and topographical variables needed to define sites may vary between climatic regions, while McEwen and Goulding (1983) have suggested that the response of trees to silviculture will depend on the factors limiting growth on that site (i.e. variables needed to define a site are likely to depend on the limiting factors).

These comments suggest that the approach of the Stand Growth Modelling Co-operative to define growth modelling regions is sound.

Future research will concentrate on three complementary areas which are described below. Research will investigate the factors causing differences in growth at the level of the site and region. New regional boundaries will be suggested by grouping sites with similar growth patterns and response to environmental variables.
Given the limited success in including environmental variables into growth models it is proposed to use currently available environmental data rather than embark on large-scale data collection before its use has been proved.

Research will look at methods for predicting growth from environmental variables. One promising approach is a multiplicative productivity index, an approach which was developed by Kiniry et al (1983). Modified forms of the original model have been developed for red pine (*Pinus resinosa* Ait.), jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), red maple (*Acer rubrum* L.) and white spruce (*Picea glauca* [Moench] Voss) (Gale and Grigal, 1988, 1990; Gale et al ,1991).

These productivity indices are based on the sufficiency (on a 0-1 scale) of certain soil characteristics in given rooting zones. The sufficiency terms are multiplied together to give the productivity index. (The shapes of these sufficiency curves are not necessarily continuous curves.) For example, the models for trembling aspen, red pine, and jack pine (Gale and Grigal, 1988) have terms for:

- sufficiency of potential available water
- sufficiency of pH
- sufficiency of climate (aridity index)
- sufficiency of slope
- sufficiency of depth to water table.

The correlations between stem volume, or mean annual increment, and productivity index are:

	Volume $ft^3\ ac^{-1}$	Mean annual increment $ft^3\ ac^{-1}\ yr^{-1}$
Red Pine	0.27(*)	0.33(**)
Trembling Aspen	0.87(**)	0.84(**)
Jack Pine	0.53(*)	0.70(**)

* significant at p=0.05 level
** significant at p=0.01 level

Volume and mean annual increment were predicted as a function of age and the productivity index.

Another approach is to define the shape of the growth curves in terms of environmental variables. For example, Grace (1980) developed a model with equations to predict diameter and height growth for Sitka spruce in U.K.. The equations were of the form:

$$Inc = R\,(CSA)^{0.5} \exp(-A\,(age-0.5)$$

where:

- R and A are parameters
- CSA is the surface area of the tree crown
- Age is the tree age at the end of the increment period
- Inc is the growth increment.

The parameter values were first estimated for each site and then (in a preliminary study) the parameters were compared with environmental variables. It was found that height growth was influenced by an oceanity classification which was based on the proximity to and influence on climate of large areas of open sea. Diameter growth was influenced by potential water deficit - the excess of potential evapotranspiration over rainfall.

A similar approach was used by Grace and Carson (1993) to develop a model for internode index in radiata pine.

Inclusion of environmental variables into models does not give a quick indication of growth potential on a site, and there is still considered to be a need for indices of productivity. Currently site index is used as such an index, however it is proving to be less than satisfactory for three main reasons. Firstly it has been found that at very low stockings, height growth of the 100 largest trees per ha is not independent of stocking (P. McLaren and G. West, unpublished results). Secondly for a given site index, the basal area growth varies around the country and on farm sites. Thirdly with the advent of improved radiata pine, one needs to compare the growth with the base level of improvement to estimate site index.

While the variability in basal area growth for a given site index has been accounted for in the model "EARLY" by defining three levels of fertility and allowing interpolation between them (West et al, 1982), there is still a need for an index of growth based on basal area or volume. Volume indices have been used in Australia and Britain. For example, South Australia has seven productivity classes which are based on the standing volume plus any volume "lost" through thinning or mortality. These productivity classes apply to a limited range of initial stockings and thinning regimes (Lewis et al, 1976).
In Britain, the yield class system is used to classify growth potential on a given site (Hamilton and Christie, 1971). The yield class of a site is the maximum mean annual volume increment that the stand attains. The time to attain the mean annual increment decreases with increasing site index. There is a close relationship between mean top height and volume production and this relationship has been used to produce top height - age curves by yield class. There are however local variations in the relationship between top height and volume production. These differences are usually assessed by considering the relationship with mean breast height diameter of the 100 trees of largest DBH per hectare. These yield classes have been derived for stands with a limited range of initial stocking and thinning regimes.

One way round the fact that basal area or volume productivity indices have been defined only for a limited range of regimes might be to define productivity in terms of a function that considers site occupancy (for example crown width, an index of leaf area) .

A promising approach is that of Horne and Robinson (1988) who considered the relationship between basal area increment and stocking using "the response increment method of analysis". They partitioned the increment into two, a time-dependent increment and a competition-dependent increment. They then determined two points on the total increment curve: the maximum stand productivity (P) and the optimum piece size (C). The promising feature of this method is that they suggest P could be used as an index of site potential for basal area growth.

RESEARCH PROPOSALS

1. Geographical Information Systems

With the increasing use of geographical information systems, there is the potential to develop maps of environmental variables that influence the growth of radiata pine. To date, maps have been produced of the nutritional status of radiata pine for nitrogen, phosphorus, potassium, magnesium and boron (Hunter et al, 1991); and for predicting site productivity decline due to forest management (Dyck et al, 1988).

One project will be to upgrade the location co-ordinates of permanent sample plots, as precise co-ordinates for the permanent sample plots are required for geographical information systems to be used effectively.

2. Growth variation between years

A better understanding of how climatic factors influence growth can be obtained by examining the relationship between the deviations in annual growth from the average trend for a given site and climatic variables at that site.

It is proposed that such a study be carried out for a number of experiments that are close to a meteorological station and that are in different regions. This would determine if response to climatic variables varies between regions. It is suggested that the Tarawera thinning trial is considered first as it is suspected that variations in climatic factors have affected growth (C. Goulding pers comm).

3. Growth variation within a region

A method of determining if environmental variables can be used to improve estimates of growth on a regional basis is to compare the errors in predicting growth in permanent sample plots using the current regional growth model with known site and environmental variables.

Two regions are suggested for this exercise:
Canterbury region: to see if environmental variables can differentiate between plains and foothills.
Nelson region: this region covers a range of climatic zones and soil types.

4. Inclusion of environmental variables in country-wide growth equations

A current research project for projecting inventory data is investigating whether environmental variables can improve equations for predicting individual tree growth.

5. Indices for classifying sites

Indices of site quality are useful in that they give an immediate idea of how trees will grow on a site. In New Zealand, site index has been used as an index of site quality. However, for a given site it has been found to decrease with low stockings. The basal area growth for a given site index also varies around the country. It is proposed to investigate whether it is feasible to develop new site quality indices for height growth and basal area growth.

It is proposed to investigate the method of Horne and Robinson (1988) as the first step towards developing an index of basal area growth.

It is proposed to investigate the trends in height growth on sites where site index has been found to vary with stocking to see whether an index of height that is common to all stockings can be found (e.g. is the age of maximum height increment common across the site?).

6. **Foliage sampling in Silviculture/Breed Trials**

Nutritional status is known to influence tree growth, and foliar P has been used to improve the Auckland Clays growth model (Shula, 1987). It is also feasible to collect foliage samples on a countrywide basis if foliar nutrient levels were found to be useful variables to include in growth models.

The silviculture/breed trials provide a set of trials with common growth and form ratings and silviculture. It is suggested that foliar nutrient levels are measured in these trials, and at a later date tree growth compared with nutrition status.

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