PREDICTING THE GROWTH OF YOUNG STANDS OF RADIATA PINE FROM SITE FACTORS

AN INVESTIGATION IN THE BAY OF PLENTY REGION

A. Wells

Report No. 16 November 1995

FOREST & FARM PLANTATION MANAGEMENT COOPERATIVE

EXECUTIVE SUMMARY

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Data from 57 permanent sample plots at 12 locations (5 ex farm sites and 7 second rotation forest sites) in young *Pinus radiata* stands in the Bay of Plenty region were used to investigate the relationships between the basal area growth level of plots in the EARLY growth model and soil and site variables. The objective was to develop a predictive growth equation based on site factors. Soil-site variables measured were rainfall, altitude, mean annual temperature, mineralisable nitrogen, Bray-2 phosphorus, C/N ratio, organic matter, texture, depth to coarse lapilli, and A horizon depth.

Analysis revealed that the plots could be separated into two discrete growth-level groupings, with the higher-growth grouping ('loam' sites) occurring on yellow brown loams and composite yellow brown pumice soils on yellow brown loams, and the lower-growth grouping ('pumice' sites) occurring on yellow brown pumice soils. The plots could be separated into these two groupings on the basis of the depth to coarse lapilli, which suggests this variable has a strong growth-limiting effect through reducing the soil volume available to tree roots.

The exceptionally high growth rates found on some of the ex-farm 'loam' sites were attributed to a large increase in soil nitrogen at these sites.

A predictive model that accouted for 77% of growth variation in 'pumice' sites was developed using depth to coarse lapilli as the predictor variable. On 'loam' sites a model accounting for 65% of growth variation using organic matter as the predictor variable was found to have a high prediction bias, and was thus poor as a predictive tool. This failure to accurately model growth is attributed to the absence of an obvious growth-limiting factor in the 'loam' site area.

The necessity in the study of dividing the dataset into two groupings suggests that the development of growth prediction equations will require sound information on soil-type influences on growth, gained through detailed soil survey.

PREDICTING THE GROWTH OF YOUNG STANDS OF RADIATA PINE FROM SITE FACTORS:
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INTRODUCTION

The aim of this project was to conduct an initial investigation into the factors related to differences in the level of basal area growth of young *Pinus radiata* on different sites. Such information is of value in assessing the ability of environmental variables to improve current growth models (Grace 1993), and in giving guidance on the likely growth of the species on unplanted sites. The latter has become especially important in recent years, with the upsurge in new investment plantings; estimates of likely productivity in such cases must generally rely on local experience and broad regional growth patterns, and are therefore often very approximate (Jackson & Gifford 1974).

Of particular importance in this respect is the ability of managers to select the appropriate basal area growth function for use in the EARLY growth model (West, Eggleston & Mclanachan 1987). While broad guidelines for each basal area function have been suggested, based on rainfall and general soil fertility, knowledge of quantifiable site factors to assist in function selection is lacking.

STUDY OBJECTIVE

The objective of this study was to investigate variation in basal area growth of young *P. radiata* stands in relation to environmental variables within the central Bay of Plenty region. The study area consists of the region centred around Rotorua, stretching roughly from Paengaroa in the north to the central Kaingaroa Plateau in the south. This includes the northern part of Kaingaroa Forest, Rotoiti and Rotoehu Forests, and areas of recently-afforested farmland (especially north of Lake Rotorua) (Figure 1).

Altitude increases over the area from about 50 m in the north-eastern corner (Paengaroa) to over 600 m in the southern section (central Kaingaroa Plateau).

The major soil-forming deposits in the area are the 'Taupo Pumice Formation' (consisting of the Taupo Ignimbrite, Taupo Lapilli and Rotongaio Ash), and the Kaharoa Ash (Pullar 1980; Rijkse 1988). North of Lake Tarawera Taupo Pumice is absent, or present only as thin traces (Rijkse 1979); in these areas the Kaharoa Ash is the major surface tephra.

The occurrence of the two main soil groups in the study area is related largely to the depth of the young coarse-textured Taupo Pumice. Where there is more than 50 cm of soil developed in Taupo Pumice, soils are classified as yellow brown pumice soils, while where Taupo Pumice is shallow (< 10 cm) or absent soils are classified as yellow brown loams (Rijkse 1988). Soils with 15-50 cm of Taupo Pumice are classified as composite yellow brown pumice soils on yellow brown loams.

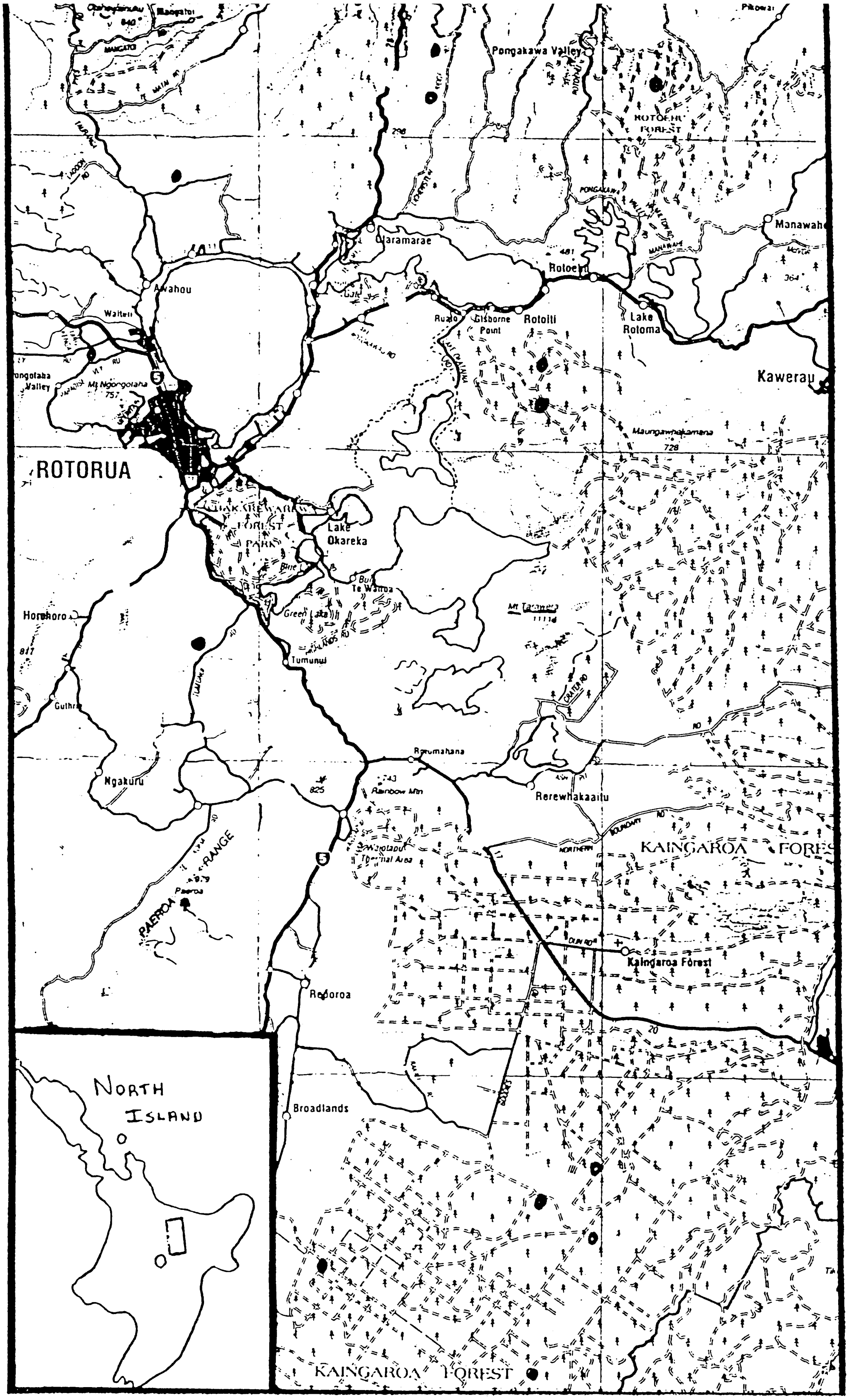

Figure 1. Location of study area.

Note: ● represents a sample point.

RELATED STUDIES

A number of other studies have attempted to relate growth of tree species to climatic, physiographic and soil variables. These can be divided into 'regional' ones including climatic variables, and 'local' ones based on physiography and soils (Madgwick 1994).

Results of thirteen predictive soil-site studies of *P. radiata* are summarised in Table 1, and give an indication of site variables used and their success in predicting growth. The most successful of these studies explain 65-90 % of variation in growth. Most of these have attributed their success to the choice of a study area in which one or two limiting and widely-varying environmental factors are present, and where all others remain relatively constant. Similarly, many detailed studies that have produced poor predictive ability have attributed the poor results to the choice of a study area with a diverse range of soils present in a climatic zone (Grey 1989).

Table 1. Summary of thirteen Pinus radiata soil site studies, showing variables used in growth prediction equations.

Source	1	2	3	4	5	6	7	8	9	10	11	12	13
Study Scale	Regional					Local							
Dependent Variable:													
Site Index	*		*	*			*					*	
Volume		*						*	*		*		
Basal area										*			*
Independent Variable:													
Rainfall	*	*	*	*	*								
Soil phosphorus	*	*	*		*	*	*					*	
soil nitrogen		*									*	*	*
soil cations			*	*									
soil calcium							*		*				
soil water													*
effective soil depth	*	*	*	*				*		*		*	
soil texture	*			*				*					
soil organic matter				*									
soil group					*								
temperature		*	*										
Model R^2		0.66	0.58		0.67	0.7	0.88		0.65	0.5	0.33	0.77	0.91

Sources

1 Czarnowski et al. 1971
2 Jackson & Gifford 1974
3 Hunter & Gibson 1984
4 Schlatter & Gerding 1984
5 Grey 1989
6 Ballard 1971
7 Truman et al. 1983
8 Turvey et al. 1984
9 Turner & Holmes 1985
10 Ryan 1986
11 Smethurst & Nambiar 1990
12 Louw 1991
13 Benson et al. 1992

METHODS

Site Selection-

Suitable plots had to have the following attributes:

* Detailed measurements of stand growth parameters from a young age;
* Detailed records of all silvicultural treatments;
* A maximum age of 14 years, and a minimum age of 5 years;
* Contain seedlings rather than cuttings;
* A stocking of 100 stems per hectare or greater.

A total of 57 suitable plots were located for use in the study.

Soil and Environmental Data-

Soil samples from the A horizon (to a depth of 20 cm) were obtained from each plot, by bulking and mixing 30 subsamples from each plot. The following tests were carried out in the laboratory:

*Mineraliseable nitrogen (anaerobic incubation technique, of Waring & Bremner (1964)), assessed at 2- and 4-weekly intervals;
*Bray-2 extractable phosphorus;
*Percentage organic matter, by loss on ignition;
*Carbon/nitrogen ratio (using a mass spectrometer).

Soil samples were also collected in each plot from the base of the A horizon to 60 cm using an auger. The following variables were measured for the samples:

*Percentage weight of material greater than 2 mm diameter;
*Texture of fine earth fraction, using the Bouocous hydrometer method (Kalra & Maynard 1991).

Other soil variables measured were:

*Depth of A horizon;
*Depth to the point at which coarse pumice lumps (lapilli greater than about 5 cm diameter) formed a continuous layer in the soil, recorded to the nearest 5 cm.

The presence of such lapilli in the profile was clearly evident, as once reached it was impossible to auger any deeper. (The depth was obtained by augering 10 holes per plot and averaging the values. It was only assessed to a depth of 170 cm, the length of the auger).

The environmental variables considered were:

*Mean annual rainfall and temperature (obtained by extrapolation of data from the nearest weather station)(New Zealand Meteorological Service 1983a; 1983b);

*Altitude (obtained from plot history sheets).

Determination of Basal Area Growth Levels in Plots-

To overcome growth variation brought about by silvicultural differences between sites (ie stocking, pruning and thinning histories), the 'basal area adjustment levels' in the EARLY Growth Model (EGM) were used as an index of stand growth. If stands are growing slightly above or below the three basal area growth functions (high, medium and low), the model allows the user to adjust the functions on a percentage basis (with a limit of 20%). The use of these percentage adjustments in effect creates a continuum of basal area increment functions from 20% below the 'low' function to 20% above the 'high' function (West et al. 1987).

On this basis a 'growth index' was formulated ranging from 100 down to 0, with each percentage adjustment in the three basal area functions of EGM representing a point on the index. The '100' level represents the maximum level of growth, and was reserved for plots in which even the highest basal area growth level in EGM (i.e. high + 20%) underpredicted growth. Nine plots were found to fall into this category; in all these cases the basal area predicted by the model was within 1-5 % of the actual basal area for the plot, and so only a very small error in plot ranking was introduced by the upper category of the index. Below 100 the basal area levels were arranged from highest to lowest - 99 equates to a level of 'high + 20%', 98 to 'high + 19%', and so on down to a score of 0 (low + 3%). All sample plots were well above the 'low + 3%' growth level, so no allowance was made for lower growth levels.

To identify the basal area function (low/medium/high ± x%) that best modelled growth in each plot, detailed stand records and mensuration data were obtained for use in EGM. Silvicultural treatments for a plot were entered prior to running the model, and growth simulation of a plot began with the model being initialised with the earliest plot measurements of diameter at breast height and mean crop height. Site index for each plot was estimated based on height data from the oldest measurement. Where plots contained genetically improved planting stock greater than GF 7, the basal area values were reduced by the appropriate proportion (G. West, pers. com.) prior to simulation, so that all plots were compared at a GF rating of 7.

The basal area level that most accurately modelled plot growth was that which gave the lowest total prediction error (ie actual minus predicted growth, for each year in which actual measurements were available).

Statistical methods

The relationships between basal area level and the 15 site variables, as well as between the latter themselves, were studied using graphical analysis and simple correlation matrices. The most promising variables in explaining growth variation were used in initial multiple regressions, using a combination of STEPWISE, FORWARD and BACKWARD procedures in the SAS statistical programme. Final regression models were developed using the standard regression procedure in SAS.

RESULTS

The distribution of sample plots in relation to location, soil type, stocking, altitude and age is summarised in table 2. Preliminary graphical analysis revealed that the sample plots could be divided into two discrete groupings on the basis of basal area level, with each group being confined to a particular soil type and altitude range. The first grouping contained all plots with a basal area level greater than 65 and occurred on yellow brown loams and composite soils below 380 m. The second grouping contained plots with a basal area level less than 55, with all plots occurring on pumice soils above 350 m. This required the two groups to be analysed as separate populations. These populations were termed 'loam' sites and 'pumice' sites, in reference to the predominant soil types on which they occurred.

The relationships between basal area and site variables were in some cases the same within both the loam and pumice groupings, and in others quite different. Variables producing the same type of relationship (but at different levels) in both groupings were measures of soil nitrogen (N, NN, TOTN)(figure 2), % silt and clay (figure 3) and measures of soil organic matter (figures 4 and 5). Different trends were produced in each grouping by the variables 'depth to lapilli' (DepthP, figure 6, DepthPco, figure 7), % coarse material (figure 8), P (figure 9), A horizon depth (DepthA, figure 10) and C/N ratio (figure 11). Altitude was the only variable to show a trend for all plots (figure 12). All other variables (i.e. % clay, MAT, RAIN, SPH, %C) showed no relationship with basal area level, either within a grouping of plots or when all plots were combined.

The basis for treating the two 'basal area level groupings' as different populations lay largely in soil type differences between them. As Table 2 shows, all of the 'higher basal area level' grouping occurred on yellow brown loams or composite yellow brown pumice soils on yellow brown loams north of Rotorua, while all but 4 of the 'lower basal area level' grouping occurred on yellow brown pumice soils south of Rotorua. The four plots in the 'low growth' grouping on composite soils (all at Tumunui Road) were noted to have a considerably thicker surface layer of young coarse-textured tephra (Taupo Pumice) than the other sites with composite soils (which had surface Kaharoa Ash); given their close proximity to 'yellow brown pumice soil' sites it was therefore considered justified to include the Tumunui sites with the plots on yellow brown pumice soils.

Summaries of variable parameters for both of the two groupings are given in tables 3, 4a and 4b.

Table 2. Distribution of Sample Plots by Location, Age, Stocking, Altitude, Site history, soil type, GF rating and Basal area level.

Location	No. of plots	Plantation age (years)	Stocking (stems/ha) range	Altitude (m)	Site history	Soil type *	GF rating	Basal area level (range)
LOAM SITES								
Valley Rd, Ngongotaha	6	9	200-400	370	Ex farm	Ngakuru sandy loam (ybl)	15	100
Jacksons Rd Kaharoa	4	9	109	370	Ex farm	Oturoa sand (composite)	15	87-100
Ridge Rd Paengaroa	16	6	350-609	60	Ex farm	Paengaroa soil (composite)	15	66-84
Branns farm Paengaroa	4	13	130-190	60	Ex farm	Paengaroa soil (composite)	14	69-100
PUMICE SITES								
Tumunui	4	8	200	350	Ex farm	Haparangi hill soils (composite)	14	41-54
Kaingaroa Forest cpt 142	8	13	150-500	550	Second rotation pine	Kawhatiwhati sand (ybps)	15	23-37
Kaingaroa Forest cpt 135	2	13	431	409	Second rotation pine	Kaingaroa loamy sand (ybps)	14	41-44
Kaingaroa Forest cpt 327	7	9	630-700	560	Second rotation pine	Kaingaroa loamy sand (ybps)	15	24-36
Kaingaroa Forest cpt 57	2	11	700	450	Second rotation pine	Kaingaroa loamy sand (ybps)	10	37-38
Kaingaroa Forest cpt 802	2	13	600	605	Second rotation pine	Kaingaroa sand (ybps)	15	18-23
Rotoiti Forest psp 50	1	14	538	590	Second rotation pine	Tarawera gravelly sandy loam (recent)	14	25
Rotoiti Forest psp 52	1	11	510	612	Second rotation pine	Tarawera gravelly sandy loam (recent)	14	14

* Soil Groups ybl = yellow brown loam ybps = yellow brown pumice soil Composite = composite yellow brown pumice soil on yellow brown loam recent = recent soil

Source: Vucetich and Wells (1978). Rijkse (1979)

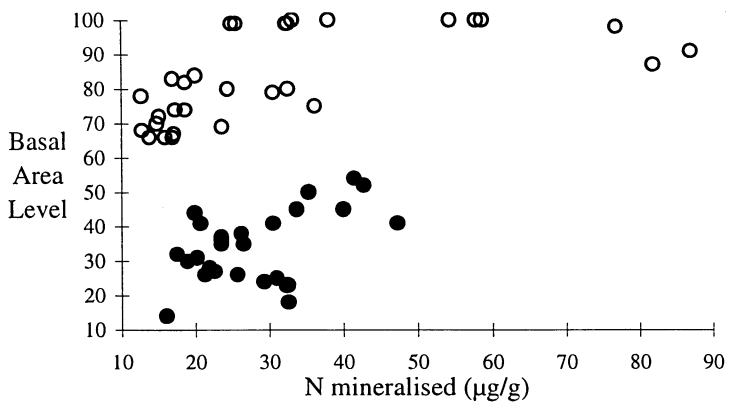

Figure 2. Relationship between basal area level and N mineralised (2 weeks), showing 'pumice' (●) and 'loam' (○) sites.
Note: A similar relationship holds for N mineralised (4 weeks) and 'NMAT'.

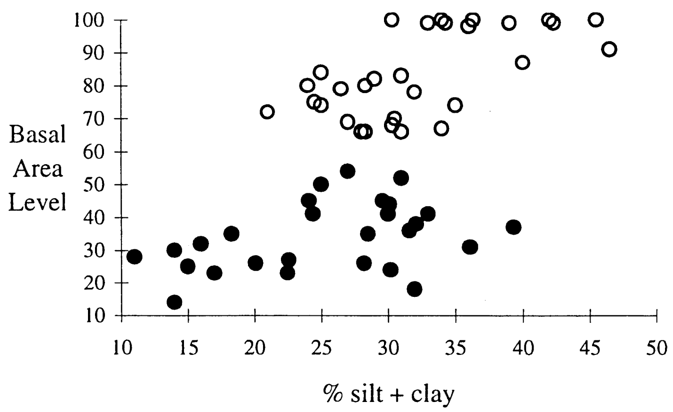

Figure 3. Relationship between basal area level and % silt + clay, showing 'pumice' (●) and 'loam' (○) sites.

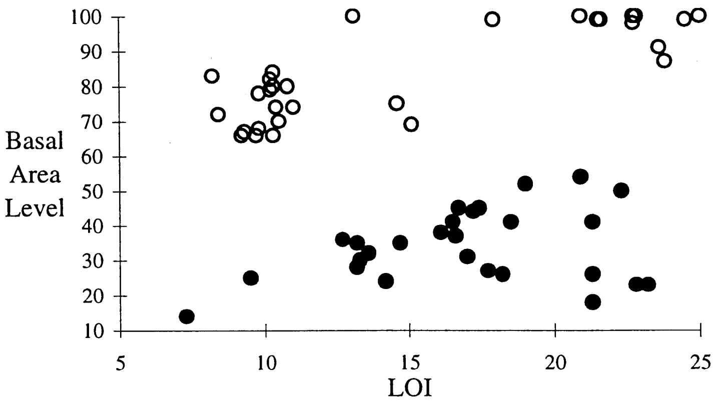

Figure 4. Relationship between basal area level and 'LOI', showing 'pumice' (●) and 'loam' (○) sites.

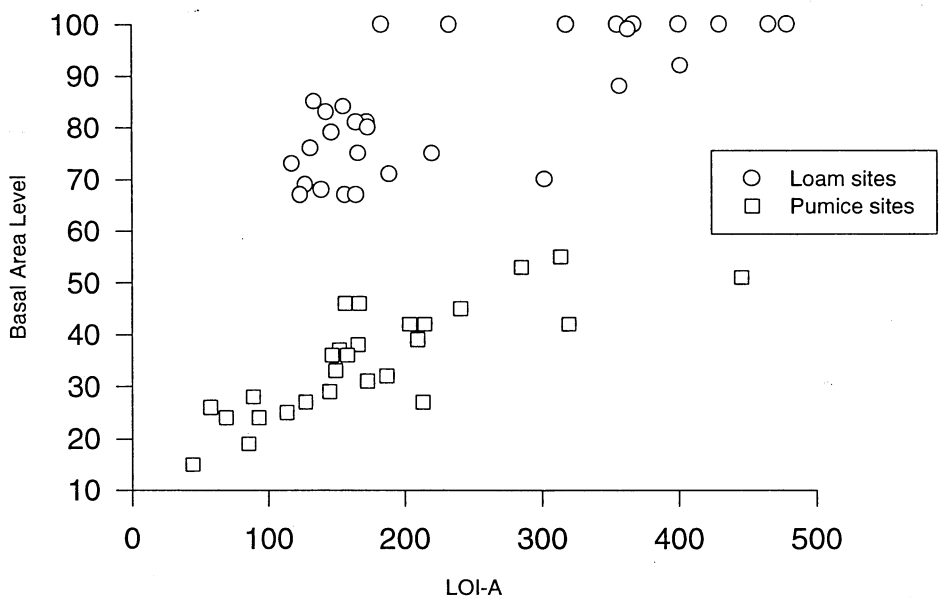

Figure 5. Relationship between basal area level and LOI-A, showing 'pumice' and 'loam' sites.

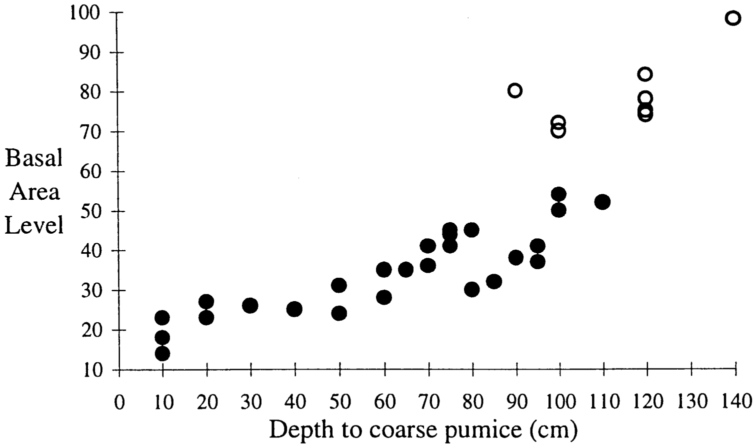

Figure 6. Relationship between basal area level and depth to coarse pumice (DepthP), showing 'pumice' (●) and 'loam' (○) sites.
Note: All 'loam' plots with a depth of greater than 170 cm are not shown.

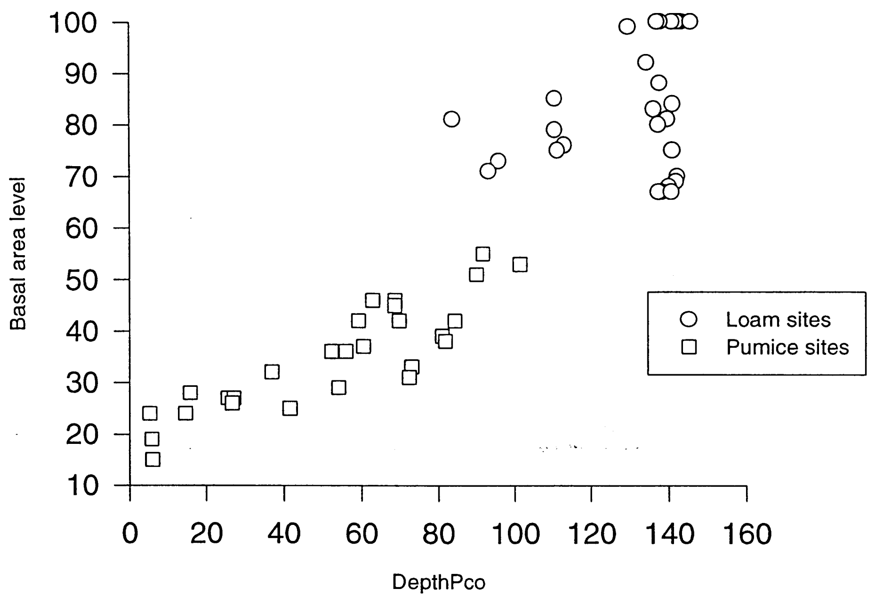

Figure 7. Relationship between basal area level and DepthPco, showing 'pumice' and 'loam' sites.

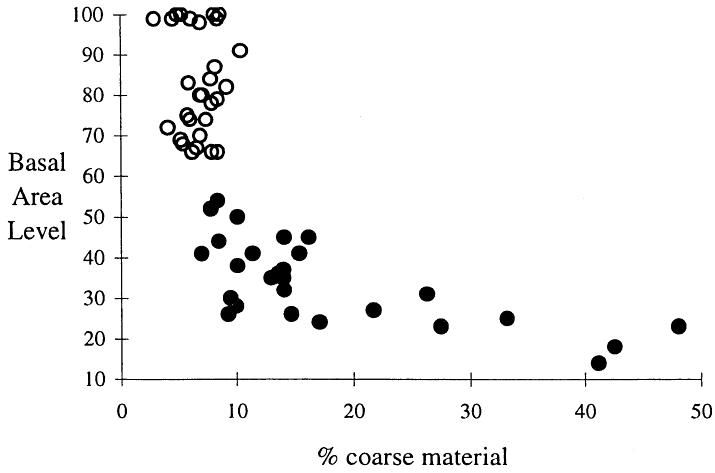

Figure 8. Relationship between basal area level and % coarse material (CO), showing 'pumice' (●) and 'loam' (○) sites.

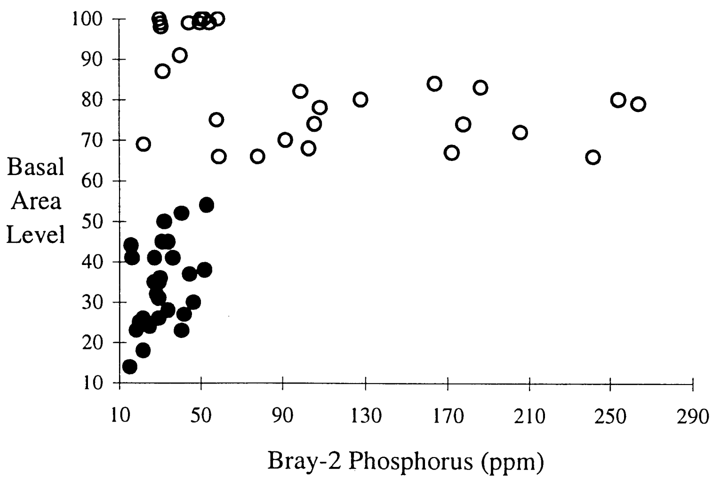

Figure 9. Relationship between basal area level and Bray-2 phosphorus, showing 'pumice' (●) and 'loam' (○) sites.

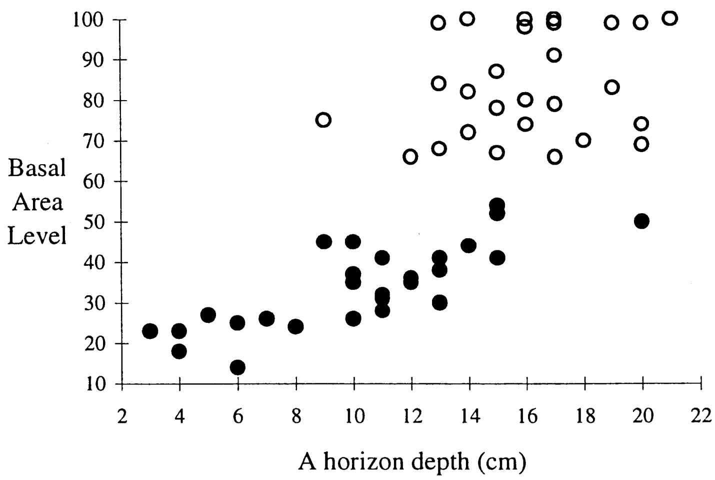

Figure 10. Relationship between basal area level and A horizon depth (DepthA), showing 'pumice' (●) and 'loam' (○) sites.

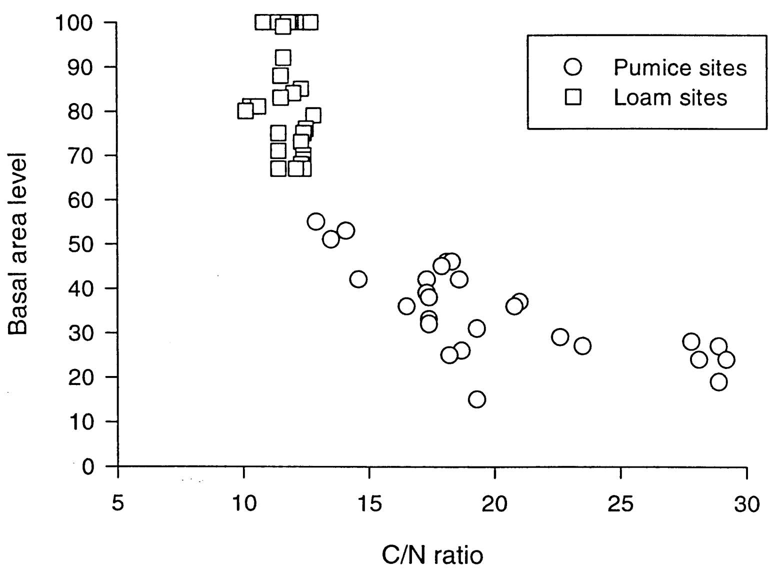

Figure 11. Relationship between basal area level and C/N ratio of the A horizon, showing loam and pumice sites.

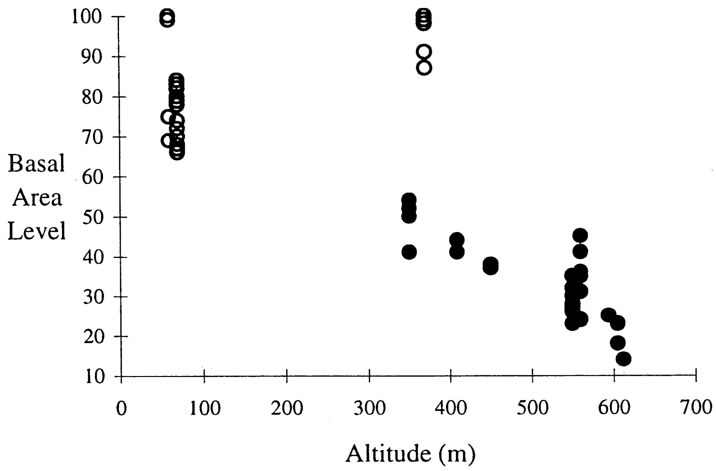

Figure 12. Relationship between basal area level and altitude, showing 'pumice' (•) and 'loam' (o) sites.

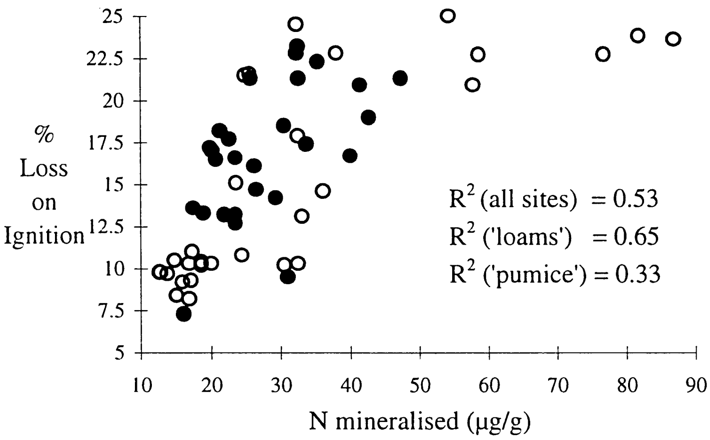

Figure 13. Relationship between loss on ignition and N mineralised (2 weeks), showing 'pumice' (•) and 'loam' (o) sites.

Simple Correlations

Simple correlations between all variables for pumice and loam sites are given in tables 5 and 6. The relationships between site variables are generally as expected. For example all three variables expressing N availability are highly significantly correlated within both groupings (but N availability and total N are not), as are measures associated with the coarse material content of the soil (DepthP, DepthPco and COARSE), soil organic matter levels (LOI, LOI-A and DepthA) and altitude (ALT and MAT). Most other significant correlations between variables appear to be chance correlations (for example LOI and RAIN, LOI and ALT, ALT and ZCL).

Measures of soil nitrogen levels (N, NN, TOTN) show significant simple correlations with basal area level in both 'pumice' and 'loam' groupings (r=0.53-0.66), as do measures of organic matter (r=0.75- 0.81). The pumice sites also show highly significant correlations between BA and depth to coarse lapilli layer (DepthP, DepthPco), % coarse material (COARSE), altitude and C/N ratio (r= -0.72). These relationships are all consistent with the plots of BA versus site variables in Figures 2-10. Within the loam sites high simple correlations are also found between BA and altitude (r=-0.78), RAIN (r=0.62), % silt + clay (r=0.61), and P (r=0.51). However, the graphs of the relationships between BA and ALT and P show that these variables are not exerting any real control over growth (Figures 12 and 9). Similarly, the small variation in rainfall between loam sites (100 mm - see Table 4b) shows that it is also an insignificant variable affecting growth between sites.

Investigation of basal area level versus silvicultural treatments (stocking, age and pruning) failed to show any significant trends.

Important soil property interrelations

The most important relationship among soil variables was found between LOI and N. As soil organic matter levels rose, so did N mineralised. This relationship is shown in Figure 13, with loam and pumice sites separated.

When all plots were combined a regression of LOI against N gave an R^2 of 0.48 ($p<0.001$). Within loam sites the R^2 rose to 0.61, but fell to 0.31 for pumice sites. When the natural logarithm of N was used in the regression the R^2 values rose to 0.57, 0.68 and 0.35 for all sites together, loam sites and pumice sites respectively.

*Table 3. Means, Standard Deviations (SD) and Minimum and Maximum Values for the Measured Site Variables (all plots). **

	Mean	SD	Minimum	Maximum
		Site and Growth Variables		
Basal area level	61	27.4	14	100
Stems/ha	465.8	236.8	109	999
Altitude (m)	331.8	210.9	60	612
Rainfall (mm/year)	1550	86.2	1450	1700
MAT (°C)	12.4	1.3	10.5	13.9
		Soil Physical Variables		
Depth A horizon (cm)	13.3	4.4	3.0	21.0
% LOI	15.9	5.2	7.3	25.0
% LOI x depth A	210.6	109.9	43.8	478.8
% clay	7.9	3.9	2.0	19.0
% silt & clay (ZCL)	28.9	7.8	11.0	46.5
% coarse material (Coarse)	11.9	9.6	2.9	48.1
Depth to coarse pumice (=Depth P) (cm)	112.8	66.8	10.0	190.0
DepthPco (cm)	104.0	55.5	5.2	155.6
		Soil Chemical Variables		
N min (2 week) (µg/g)	30.1	16.3	12.7	86.9
N min (4 week) (µg/g)	67.5	28.8	27.7	158.3
N x MAT (µg/g)	360.0	203.6	158.7	1104.0
Total N (%)	0.43	0.17	0.18	0.89
Total C (%)	6.2	1.6	3.5	10.3
C/N ratio	15.6	5.3	10.1	29.2
Bray- 2 P (ppm)	67.6	64.1	15.1	263.9

* see Appendix 1 for full definition of terms

*Table 4A. Means, Standard Deviations (SD) and Minimum and Maximum Values for the Measured Soil Variables : Pumice Sites **

	Mean	SD	Minimum	Maximum
		Site and Growth Variables		
Basal area level	35.1	10.4	15	54
Stems/ha	597.9	234.1	188	999
Altitude (m)	513	86.7	350	612
Rainfall (mm/year)	1472	47.3	1450	1654
MAT (°C)	11.1	0.3	10.5	11.5
		Soil Physical Variables		
Depth A horizon (cm)	10.3	4.0	3.0	20.0
% LOI	16.9	4.0	7.3	23.2
% LOI x depth A	174.9	89.7	43.2	445.0
% clay	6.3	3.1	2.0	13.0
% silt & clay (ZCL)	25.3	7.5	11.0	39.3
% coarse material (Coarse)	17.7	11.4	7.0	48.1
Depth to coarse pumice (=Depth P) (cm)	61.3	30.7	10.0	110.0
DepthPco (cm)	53.1	28.8	5.2	101.4
		Soil Chemical Variables		
N min (2 week) (µg/g)	28.0	8.3	16.1	47.3
N min (4 week) (µg/g)	54.1	12.4	34.5	80.4
N x MAT (µg/g)	311.8	95.3	169.1	543.9
Total N (%)	0.33	0.10	0.18	0.57
Total C (%)	6.3	1.4	3.5	8.8
C/N ratio	19.9	4.9	12.9	29.2
Bray- 2 P (ppm)	31.2	10.6	15.1	53.0

* see Appendix 1 for full definition of terms

*Table 4B Means, Standard Deviations (SD) and Minimum and Maximum Values for the Measured Site Variables : Loam Sites **

	Mean	SD	Minimum	Maximum
		Site and Growth Variables		
Basal area level	84.3	12.7	66	100
Stems/ha	346.9	168.1	10.9	630
Altitude (m)	168	144.3	60	370
Rainfall (mm/year)	1620	40.7	1600	1700
MAT (°C)	13.4	0.7	11.5	13.9
		Soil Physical Variables		
Depth A horizon (cm)	16.0	2.7	9.0	21.0
% LOI	14.9	6.1	8.2	25.0
% LOI x depth A	242.7	117.4	117.6	478.8
% clay	9.4	3.9	4.5	19.0
% silt & clay (ZCL)	32.3	6.5	21.0	46.5
% coarse material (Coarse)	6.8	1.7	2.9	10.4
Depth to coarse pumice (=Depth P) (cm)	160.0	19.1	90.0	170.0
DepthPco (cm)	150.8	17.9	83.6	165.6
		Soil Chemical Variables		
N min (2 week) (µg/g)	32.0	21.1	12.7	86.9
N min (4 week) (µg/g)	69.9	38.2	27.7	158.3
N x MAT (µg/g)	422.2	262.9	158.7	1104.0
Total N	0.53	0.16	0.29	0.89
Total C	6.1	1.8	3.6	10.3
C/N ratio	11.8	0.7	10.1	12.8
Bray- 2 P (ppm)	100.4	74.0	20.3	263.9

* see Appendix 1 for full definition of terms

Table 5. Significant Simple Correlations Between Site Variables - 'pumice sites'.

*Note: All Correlations Shown are Significant (p<0.01), Unless Indicated * where p<0.05*

See Appendix 1 for definitions of variables.

	BA	N	Log (N)	NN	NMAT	P	LOI	LOI-A	Depth A	Depth P	DepthPco	Coarse	Clay	XCL	Alt	Rain	MAT	SPH
BA	1																	
N	0.62	1																
Log (N)	0.61		1															
NN	0.58	0.63	0.51	1														
NMAT	0.53	0.99	0.95	0.53	1													
P	0.39*					1												
LOI		0.56	0.50		0.55		1											
LOI A	0.81	0.45*	0.43		0.47*			1										
Depth A	0.8							0.91	1									
Depth P	0.88					0.46*		0.76	0.87	1								
Depth P co	0.88					0.48*		0.78	0.88	0.99	1							
Coarse	-0.7							0.66	-0.78	-0.77		1						
Clay													1					
Zcl	0.4*												0.44*	1				
Alt	-0.75							-0.86	0.78	-0.74		0.61			1			
Rain																1		
MAT	0.66					0.43*		0.54		0.69	0.68	-0.77			-0.55		1	
SPH	-0.42*	-0.45*			-0.46*										0.66			1

Table 6. Significant Simple Correlations Between Site Variables - 'loam sites'.

*Note: All Correlations Shown are Significant ($p<0.01$), Unless Indicated * where $p<0.05$*

See Appendix 1 for definitions of variables.

	BA	N	Log(N)	NN	NMAT	P	LOI	LOI-A	Depth A	Depth P	DepthPco	Coarse	Clay	XCL	Alt	Rain	MAT	SPH
BA	1																	
N	0.60	1																
Log(N)	0.69		1	1														
NN	0.65	0.90	0.91	1														
NMAT	0.59	0.99	0.99	0.95	1													
P	-0.51	-0.51	0.49	0.49	-0.51	1												
LOI	0.81	0-78	0.81	0.8	0.76	-0.7	1											
LOI A	0.75	0.63		0.7	0.61	0.6	0.94	1										
Depth A								0.54	1									
Depth P										1								
Depth P co										0.99	1							
Coarse												1						
Clay													1					
Zcl	0.61	0.61	0.61	0.52	0.44	-0.53	0.78	0.79		0.45*	0.44*		0.7	1				
Alt	-0.78	0.73		0.75	0.7	-0.57	0.93	0.91						0.74	1			
Rain	0.62						0.67	0.72				-0.47		0.52	0.71	1		
MAT	0.48	-0.52		-0.54	-0.48		-0.69	-0.7						-0.6	-0.76	-0.54	1	
SPH	-0.46	-0.59	-0.56	-0.67	0.7	0.66	-0.67	-0.54							-0.51			1

A strong linear relationship was also found between N (N mineralised in 2 weeks) and NN (N mineralised in 4 weeks). In almost all soils the 4-week N production was very close to double the 2-week N production .

A relationship also existed between DepthP and COARSE. When the reciprocal of DepthP was used, regression analysis gave an R^2 of 0.80 ($p<0.001$).

No consistent trends could be observed between soil chemical properties and aspects of site management history (i.e. stocking, pruning, past land use or stand age). However, as is evident from Figures 2, 9 and 11, some ex-pasture sites stand out as having significantly greater levels of available N and P and low C/N ratios.

Regression Analysis

<u>All plots combined</u>

To allow analysis of all plots together, a dummy variable "soil type" was used to separate the loam sites from the pumice sites. Initial regression modelling using variables with the same relationship in both soil types found 'N' and 'LOI-A' to be the only variables incorporated in the equation at the 0.1 level of significance. At the 1% level of significance, only soil type and 'LOI-A' were included in the equation. The regression model based on this variable is given in Table 7a.

Analysis of the residuals of the equation revealed two outliers in the data, both of which were from the one site (Brann's farm). Examination of the dataset showed these two plots to have very low levels of organic matter compared with other sites growing at the same basal area level (90-100). The reasons for this are not clear; however both plots were located on sites with a very steep gradient (in contrast to other plots), which may have hindered the accumulation of organic matter.

The regression model following the removal of these two plots is given in Table 7b. The mean square error of the model decreased by 1.32 to 6.21, with an R^2 of 0.95. A comparison of actual basal area level versus basal area level predicted by equation 7a is shown in Figure 14. This relationship reveals a definite bias in prediction of BA for the loam sites. At lower basal area levels within this grouping (<75), BA is consistently overpredicted, while at moderate levels (76-85) BA is consistently underpredicted; above this level no obvious trend is apparent. Thus for loam sites the equation developed using 'LOI-A' cannot accurately separate growth levels between 67 and 85.

The different relationships found between some variables and basal area level made it necessary to also formulate regression models for each soil type separately.

Table 7. Multiple Regressions of Basal Area Level Against Site Variables.

		Coefficient	Standard Error	t	R^2
7a	Intercept	63.56	2.71	23.4	
	Soil Type (dummy)	43.42	2.10	-20.6	0.82
	LOI-A	0.09	0.01	8.9	0.11
	MSE		7.53		0.93
7b	Intercept	61.87	2.28	27.2	
	Soil Type (dummy)	42.48	1.77	-23.9	0.82
	LOI-A	0.09	0.01	11.3	0.13
	MSE		6.21		0.95

Pumice sites

Initial regression runs reduced the number of variables of importance to the two most significant: 'N' and 'DepthPco'. All other variables showing a high simple correlation coefficient were related to these two variables, preventing their continued use. For example DepthP, COARSE, ALT and DepthA and C/N were all highly correlated with DepthPco, and NMAT, NN and LOI with N. The two variables selected made the greatest independent contribution to explaining basal area level within these groups.

The two final regression models developed for the 'pumice sites' are summarised in Table 8a and 8b. Addition of the variable 'N' to the model does not greatly improve the standard error or R^2, and the variable itself has a low t value (significant at the 0.05 level).

Table 8. Multiple Regressions of Basal Area Level Against Site Variables - pumice sites.

		Coefficient	Standard Error	t	R^2
8a	Intercept	18.26	2.06	8.9	
	Depth Pco	0.32	0.03	9.3	0.77
	MSE		5.04		
8b	Intercept	11.49	3.24	3.5	
	Depth Pco	0.29	0.03	8.9	0.77
	N	0.29	0.11	2.6	0.05
	MSE		4.56		0.82

Loam sites

Initial regression runs selected only two variables that were significant at below the 0.2 level. These were LOI and LOG(N). Other variables with high significant simple correlations with basal area level (NN, NMA, TOTN, P, ALT, RAIN, MAT and LOI-A) were found to make insignificant independent contributions to variation in site productivity, due to their collinearity with LOI or LOG(N).

The two variables selected for further analysis were also highly interrelated (r=0.82). LOI was subsequently found to be the more important variable, giving the equation in Table 9a.

Table 9. Multiple Regressions of Basal Area Level Against Site Variables - loam sites.

		Coefficient	Standard Error	t	R^2
9a	Intercept	59.14	3.77	15.7	
	LOI	1.69	0.23	7.2	0.65
	MSE		7.69		
9b	Intercept	11.49	3.24	3.5	
	LOI	1.69	0.19	8.9	0.76
	MSE		6.23		

Analysis of residuals again revealed two outliers in the data, these being the same plots as before. Their removal from the dataset substantially improved the R^2 and decreased the standard error of the regression equation (Table 9b).

A comparison of actual BA versus BA predicted by equation 8b (pumice sites) and 9a (loam sites) is shown in Figure 15. Prediction of BA at loam sites is again biased. When N was used as the predictive variable instead of LOI for loam sites, a similar trend in residuals was found. In contrast with loam sites, prediction of BA for pumice sites using the variables DepthPco and N is free of bias.

DISCUSSION

Accuracy of Basal Area Level Index-

The validity of the study's results depend to a large extent upon the accuracy of the "basal area level index" in representing the relative growth rates of plots adjusted for stocking and management practices. As the results of this study and of West et al. (1987) show no indication of trends in basal area level associated with age, stocking, pruned height or thinning history, the assumption that the EGM accurately ranks growth adjusted for silviculture seems justified. The adjustments used for genetically improved planting stock are perhaps less well established; however the fact that all but two of the plots contained planting stock of GF 14 or 15 (Table 2) means that errors resulting from adjustments will be insignificant.

Success of Predictive Equations-

The primary objective of this study was to investigate whether the productivity of a site (in terms of basal area level in EGM) could be predicted confidently from measurable soil properties. The results obtained do go some way to fulfilling this aim.

The regression equations derived for all sites combined and for pumice sites separately have an overall error level of ±10-15%, or between ±4.6-7.5 'basal area level' adjustments, with R^2 values above 0.75. When loam sites were modelled separately the error level rose to above 20%, indicating the inadequacy of all the measured soil variables in explaining growth variation on these sites.

While the data in this study can be merged to create a single model based on one equation using fewer variables, the separation used in dividing the sample into loam and pumice sites maintains a level of differentiation that clearly exists based on early growth of *P. radiata*, as well as on soil profile characteristics.

The most obvious differences between the two site groupings in terms of soil properties can be drawn from Figures 2-12. Firstly it should be noted that none of the properties measured except for DepthP, COARSE and C/N provide a satisfactory basis on which to separate the data into the two site groupings. While the mean values for N, TOTN, P, DepthA, ZCL and LOI are all higher for the 'loam' grouping the range of values between groups are always overlapping to a large extent. Certainly some of the most productive loam sites do have the highest levels of N, C/N and P, but the relationship is not general. Similarly the four ex-farm sites on pumice soils show relatively high levels of these variables, but basal area level is much lower than on loam sites with similar nutrient levels. For a given level of N, P, LOI, DepthA or ZCL, productivity is significantly lower on pumice compared with loam sites; basal area is in effect moved to a higher plain on loam sites while maintaining the same general relationship with most soil properties. The complete separation of basal area levels between the two groupings cannot therefore be attributed to greater levels of these soil properties.

In contrast with the above variables, measures associated with soil 'coarseness' and lapilli content allow an almost perfect differentiation between loam and pumice sites. The depth to 'continuous lapilli' for example, was under 115 cm at all 'pumice sites', but was greater than 170 cm at all but six of the 'loam sites'. Similarly pumice sites show a mean proportion of coarse material in the subsoil that is almost three times that of loam sites (17.7% compared with 6.8%). These results strongly suggest that soil physical properties are a major factor causing the marked productivity differences between soil groupings. This conclusion is strengthened by the highly significant and close relationship found between basal area level and DepthP on pumice sites, suggesting this to be the major growth-limiting factor on these soils.

This interpretation is potentially confounded, however, by the close correlation found between ALT and DepthP (r=-0.74). It is unlikely though that the small altitudinal differences could result in the consistent growth changes found when other environmental factors are varying widely. Nevertheless it is true that at least a portion of the variation in growth apparently explained by DepthP may actually be due to the influence of altitude.

A further important point to note is that the C/N ratio of the A horizon allows for the perfect separation of plots into loam and pumice groupings, with no overlap (figure 10). This at first suggests that the lower C/N ratios may be the critical factor explaining the higher growth levels on loam sites. However, closer examination of the data makes this unlikely.

A more likely explanation lies in the differentiation between ex-farm and forest sites. The four 'pumice' sites with the highest C/N ratios are the Tumunui plots, these all being ex-farm sites; as figure 10 shows, on the basis of C/N ratio these plots are better placed within the 'loam' (ex-farm sites) grouping, leaving all other 'pumice' sites (forest sites) as a separate group. This creates the problem of the Tumunui sites having much lower basal area growth than the loam sites despite having basically the same C/N ratio, which strongly suggests that the C/N ratio is not the crucial variable giving rise to the two basal area groupings.

The variation in C/N ratios in this study is therefore an artefact of the farming history on some of the sites, with the soil physical differences between the sites being the major driving factor behind growth variation between the groupings. Nevertheless, the relation between basal area and C/N on pumice sites (r= -0.78) suggests that C/N still plays a role in limiting growth in the study area.

There is, however, some evidence to suggest that unmeasured soil chemical differences between sites may be playing a part in the growth differences between loam and pumice sites. This evidence relates to the sites at Valley Rd (high-growth loam site) and at Tumunui (moderate-growth pumice site); both these trials have similar silvicultural regimes and altitudes, but the Tumunui plots have shown signs of severe magnesium deficiencies following pruning (G. West and B Manley, pers. comm.). This suggests that there could be differences in soil chemical properties that were not measured in the study, but which are affecting relative growth rates at the sites.

The importance of soil properties for tree growth

It is important now to consider the reasons for the influence of the site variables on the growth of *P. radiata.*

1. Soil physical properties

Without doubt, 'DepthP' is the most influential factor found in the study. 'DepthP' relates well to the concept of "effective soil depth" used in other studies. This is usually defined as the depth of soil to an impediment to root exploration, which may take the form of unsuitable soil water conditions or a physical barrier such as bedrock or a fragipan. Some measure of effective rooting depth has consistently featured as a major factor correlating with *P. radiata* growth in previous studies (Table 1),

Although all of these studies have considered 'effective soil depth' to be defined by a layer through which tree roots are unable to penetrate or, in the case of anaerobic conditions, below which roots are unable to survive, the major implication of the concept is that the soil volume available for root development and exploitation of minerals and water is reduced. Thus, although the coarse pumice layer defined in this study is unlikely to be an absolute barrier to root penetration it does represent a depth below which roots will have a very limited proportion of fine earth to explore, and as such it can be regarded as representing the 'effective soil depth'. This is supported by the fact that the variable 'DepthPco', representing an adjustment of soil depth to account for the proportion of coarse-textured material (>2 mm) above the lapilli layer, accounted for slightly more variation in productivity than DepthP.

The beneficial effects of a greater volume of fine soil for root development occur through increasing the potential for uptake of moisture and nutrients. Most New Zealand researchers have considered water shortage on pumice soils to be an insignificant factor. Will (1965), for example, stated that even during the severest of droughts in the area moisture uptake would not be restricted to the extent of affecting tree growth, Despite this, it is possible that growth may be restricted by inadequate nutrient uptake when the surface layers are near wilting point, especially in soils with a low clay content in which persistent dry patches can develop .

The validity of interpreting DepthP as equating to an 'effective soil depth' could be questioned, on the grounds that tree roots can presumably grow through the soil layer dominated by lapilli into more favourable textures below. However in young trees root development is unlikely to have reached such an extent, and so uptake of water and nutrients will be entirely from the top section of soil. Consequently where the lapilli layer is closer to the surface young trees will have access to considerably less favourable soil than where the layer is deeper or absent, which will certainly influence relative growth rates between sites. Thus, even if in mature stands tree roots are able to gain access to soil below the lapilli layer, the volume of soil above this layer is undoubtedly important for early tree growth before root systems have developed sufficiently to dominate the site.

Organic matter

The quantity of organic matter in the A horizon appears to be an important factor related to growth in this study, giving significant correlations with productivity for both loam (r=0.8) and pumice (r=0.81)sites.

Organic matter is vital in soils. It influences water availability through effects on water retention, resistance to water flow and extent to which tree roots can explore the soil, and represents the major pool of plant nutrients that become available through mineralisation (Sands 1982).

The importance of organic matter in this study is illustrated by the relationship found between LOI and N mineralised (Figure 13). In both site groupings N mineralised increases with soil organic matter content. This is consistent with the fact that production of ammonium-N in soils is dependent upon mineralisation, the breakdown of complex organic compounds by micro-organisms (Bowen and Nambiar 1984).

The reason for the failure of 'LOI' to model 'loam site' basal area level without bias is evident from Figure 4. While a trend of increasing BA with LOI is evident, the relationship is rather clumped -i.e. the loam sites can be split into two broad subgroups based on LOI, with one group centred around 10% LOI and the other around 20%. Within this first grouping, basal area level of individual plots varies widely (from 66 to 84), yet LOI only ranges between 9 and 14%, with no pattern relating to BA. All plots within this LOI range are thus given basically the same predicted growth level, and so the model is poor as a predictive tool.

The relationships found between pine productivity and 'effective soil depth' and soil organic matter content have important implications for site management practices to ensure maintenance of site productivity on these soils. Any management activity that results in the loss or redistribution of fine soil particles and topsoil will clearly be detrimental for growth, especially on the pumice soils.

2. Soil chemical properties

Nitrogen

On the loam sites BA apparently rises with N availability, before reaching a plateau level beyond which extra N has little effect (Figure 2). The most interesting observation about the relationship found on loam sites, however, is that the plots can be divided into two distinct subgroupings on the basis of N (figure 2) and TOTN, in the same way they could be on the basis of LOI. Plots with a basal area level of 90 or above form a subgroup with noticeably higher levels of total and 'available' N and organic matter than the other loam sites.

This strongly suggests that a marked increase in the levels of soil N at these sites compared with other 'loam' sites has caused their greater growth levels. The increase in nitrogen is presumably brought about by greater fertiliser inputs and N fixation by clover at these sites than at other farm sites.

The linear relationship found between basal area and N on pumice sites suggests that N is a limiting factor for growth on these soils. The weakness of the relation (R^2=0.3, $p<0.05$) however, reflects the much greater control of physical properties on tree growth.

Phosphorus

The poor relationship between available P and productivity is clearly shown by Figure 6. This result reflects the generally moderate levels of P found at all the sites- in all plots the P extracted was greater than 15 ppm, with most plots above 25. This compares with a level of 12 ppm regarded as "adequate" for growth of *P. radiata* in New Zealand (Rijkse 1988).

The very high P levels found on some of the ex-pasture sites is consistent with past studies (Walker, Thapa & Adams 1959; Skinner & Attiwill 1981), and reflects the addition of phosphate fertilisers.

The importance of study area

The necessity in this study of dividing the original dataset into two groupings stratified on the basis of soil type emphasises the importance of choosing a relatively uniform area if soil-growth studies are to be successful. To demonstrate significant variables affecting growth it is necessary to measure limiting and widely varying environmental factors, while holding all others constant (Stone 1984). This is clearly far easier when the study area is small and relatively homogenous with respect to climatic and soil conditions.

Reasons for success/failure of regression models

The ability to demonstrate significant soil-growth relationships on the 'pumice sites' can be explained in terms of the above discussion on study area. All the sites were in the same altitudinal zone (400-600 m), all except two were on flat sites, and all occurred on the same soil parent material (Taupo Pumice Formation). These factors resulted in a relatively homogenous area. Secondly, a limiting factor (relating to soil volume and texture) was present at all sites, and varied widely. Almost all studies displaying high correlations between growth and soil have similarly included only one or two variables of overriding importance in the final equation (for example, Czarnowski et al. 1971 (texture); Turvey et al. 1986 (soil depth and % sand); Truman et al. 1983 (Ca + P); Turner & Holmes 1985 (Ca); Ryan 1986 (soil depth)).

The failure to demonstrate any close relationships between soil properties and growth on 'loam sites' is less easy to account for. One factor may have been the lack of an obvious limiting factor at these sites. The highest-growth plots for example, showed the highest levels of N, P, % silt and clay, organic matter and A horizon depth, and the lowest levels of coarse material in the soil profile. Rainfall and altitude were also favourable. With growth factors so uniformly favourable it is very difficult to explain growth variation on the basis of one or two variables of overall importance.

Another reason may lie in the nature of the landscape sampled. The area containing the 'loam' plots is topographically and geomorphologically more diverse than the 'pumice site' area. For example, the plots selected in this study occurred on a variety of aspects, slope steepness levels and slope positions (e.g. valley floors, sideslopes and gullies). In an area of high tree growth potential with no one clearly-limiting factor, the above factors of a site may be very important in accounting for growth variation, through their influence on microclimate and soil water and nutrient gradients.

CONCLUSIONS

The analyses undertaken show that there is potential for growth models to be improved by incorporating environmental variables into the modelling. This is shown by the fact that on 'pumice' sites the measured soil variables were able to account for over 75 % of the variation in basal area level.

The necessity of dividing the sites sampled into two groupings has important implications for future growth-prediction studies. It shows that different soil properties are determining growth within the two site groupings; to allow good growth prediction it is therefore necessary that information on soil type and variability is incorporated into prediction equations. In this respect detailed soil survey is a prerequisite for developing and improving upon growth prediction models.

The importance of soil physical properties for early tree growth within the study area was also highlighted. The increase in growth on 'pumice' sites with increasing depth to lapilli demonstrates the growth-limiting effect of a decreased soil volume for root development in young trees, and the importance of using management techniques that cause the least possible site disturbance.

The very high basal area growth levels found on some of the ex-farm sites can be attributed to highly favourable soil physical conditions and markedly greater levels of soil nitrogen.

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APPENDIX 1

EXPLANATION OF SITE VARIABLES USED IN STUDY.

Variable Abbreviation	Variable description/derivation
Soil Chemical Variables:	
N	Nitrogen mineralised during a two-week anaerobic incubation, at 30°C (ug/g of soil).
NN	Nitrogen mineralised during a four-week anaerobic incubation, at 30°C (ug/g of soil).
NMA	= N x M.A.T. Represents an adjustment of laboratory mineralisation values for field temperatures.
LOG(N)	Natural logarithm of N.
P	Phosphorus level of the A horizon (ppm), as determined by Bray-2 extraction.
TOTN	Total nitrogen (%) of A horizon, measured by mass spectormeter.
CN	C/N ratio of the A horizon.
TOTC	Total carbon (%) of A horizon, measured by mass spectrometer.
Soil Physical Variables:	
Depth A	Depth of the A horizon, measured to the nearest cm.
LOI	% loss on ignition of the A horizon, an estimate of soil organic matter content.
LOI-A	= LOI x DepthA. Represents an index of total organic matter levels between sites.
Coarse	% of B horizon material greater than 2 mm diameter (by weight).
DepthP	Depth to coarse pumice lumps (lapilli) greater than 5 cm diameter.
DepthPco	= DepthP - (Coarse/100 x DepthP). Represents an adjustment of DepthP, to take account of soil space unavailable for root occupation.
Clay	% of fine earth soil fraction consisting of clay-sized (<0.002 mm diameter) particles.
ZCL	% of fine earth fraction consisting of clay-sized (<0.002 mm diameter) and silt-sized (0.002-0.05 mm diameter) particles.

Other Site Variables:

Alt	Altitude, in metres above sea level.
Rain	Mean annual precipitaiton (mm).
MAT	Mean annual temperature (°C).
Aspect	Site aspect, expressed as one of the eight major points of the compass.

Stand and Growth Variables:

BA	Basal area level function used in the Early Growth Model, expressed on an index from 0-100.
SPH	Stand stocking, in stems per hectare.