

NUTRIENT RELATIONSHIPS OF RADIATA PINE IN TASMAN FOREST, NELSON

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ABSTRACT

A combination of soil and foliar analyses, simple correlation analysis, and stepwise linear multiple regression analysis was used to investigate growth differences within second rotation, regenerated radiata pine (*Pinus radiata* D. Don) stands on Mapua hill soils in Tasman Forest, Nelson. The soils have very low levels of most plant nutrients but accumulation sites such as gully bottoms and steeper slopes have been rejuvenated by deposition and erosion processes respectively. These sites thus tend to have a slightly higher nutrient status than the eroded main and spur ridges. This is reflected in better tree growth. The data suggest that phosphorus deficiency, nitrogen deficiency, and high manganese uptake resulting from high soil acidity are the most important nutritional factors limiting growth of radiata pine on hard sites. A close relationship between phosphorus and nitrogen nutrition was indicated. It is suggested that with adequate additions of phosphate and lime, the nitrogen balance of the system could be improved by increasing the rate of mineralisation of soil organic matter to an extent where additions of nitrogen would be unnecessary. A critical foliar level of approximately 700 ppm is indicated for manganese toxicity in radiata pine in Tasman Forest.

INTRODUCTION

The Nelson Province is one of the main areas of exotic forestry in New Zealand. The bulk of this forestry is concentrated in Waimea County where over 30 000 ha are planted, mainly in radiata pine (*Pinus radiata* D. Don). The history of forestry in the area has been briefly described by Appleton & Slow (1966).

Nutritional problems in radiata pine growing on soils developed on the Moutere Gravels in Nelson have been frequently discussed since the early 1960s. The problems can be broadly divided into two types:

(i) Second rotation stands apparently have a slower initial growth rate than first rotation stands. Although an insufficiency of data on the first rotation makes comparisons difficult, slower growth rates in the second crop seem to be limited to the hardest sites such as ridge tops (Whyte, 1973). Whyte considers the apparent drop in productivity

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to be mostly transitory, representing the extension of an initial period of stagnation in second crops compared with the first.

(ii) Significant areas in both first and second rotation stands show nutrient deficiency symptoms (Verey & Biggs, 1952; Appleton & Slow, 1966). Nutritional disorders are perhaps the most prominent problem in Nelson forestry. A number of deficiencies have been identified in earlier studies in the Tasman and Waiwhero forests on the Moutere Gravels. These include boron, nitrogen, phosphorus, and possibly magnesium (Will *et al.*, 1963; Stone & Will, 1963, 1965a, 1965b; Appleton & Slow, 1966). Suggested fertiliser programmes to alleviate nutrient deficiencies in Tasman Forest have been developed from the results of pilot field trials using treatments based largely on limited foliar analyses and visual deficiency symptoms.

The present study has investigated possible nutritional reasons for observed growth differences in second rotation radiata pine regeneration in Tasman Forest in greater detail than previous studies. The paper discusses possible nutrient deficiencies suggested by foliar nutrient levels, soil chemistry, and soil-foliar correlations. Stepwise linear multiple regression analysis between an index of tree size and foliar nutrient levels was used to provide further information on possible nutrient interactions influencing tree growth. Gentle and Humphreys (1968) consider that where plantings covering a range of site qualities are available, this combination of techniques provides the most reliable diagnostic guideline to estimate nutrient availability in forest soils.

Present growth of second rotation regenerated radiata pine in Tasman Forest is closely correlated with topographic position (Kingston, 1968). Poor growth commonly occurs on ridge tops with good growth in the gullies and on steeper slopes. Kingston has shown that 49% of the variation in site index in Tasman Forest can be accounted for from physical and morphological soil properties. The topographic units delineated by Kingston were used as the basis for the sampling programme in this study.

SOILS AND SOIL-FORMING FACTORS

Within the study area the soils vary too widely to permit classification as one soil type. They have been mapped as Mapua hill soils, related to the Mapua sandy loam found on gentler slopes (Chittenden *et al.*, 1966). The soils are classified as strongly weathered and leached intergrade yellow-grey to yellow-brown earths from preweathered Moutere Gravels. The deeply weathered parent material and the prevalence of erosion have led to the development of soils depleted in many plant nutrients.

The parent material is the Moutere Gravel Formation. These Pleistocene gravels consist of deeply weathered, well-rounded, pebbles and cobbles of quartzose greywacke in a clay-sand matrix (Henderson *et al.*, 1959).

Mean annual rainfall at Harakeke in Tasman Forest is 983 mm (New Zealand Meteorological Service, 1968). Mean maximum and minimum temperatures at Appleby, 16 km south-east of Harakeke are 17.0°C and 7.3°C respectively. This climate provides good conditions for radiata pine growth.

Pre-European vegetation on Mapua soils probably consisted of manuka (*Leptospermum scoparium*) and stunted bracken fern (*Pteridium aquilinum* var. *esculentum*) with patches of beech (*Nothofagus* sp.), flax (*Phormium tenax*), and toe-toe (*Cortaderia* sp.) in the gullies (Rigg, 1952). Extensive apple and pear orchards were planted from 1911 to 1916, but many were abandoned and later replanted in radiata pine. Many present exotic forests date from this period.

The landscape in Tasman Forest consists of a series of broad, gently sloping main ridges separated by very broad, almost level gullies. Broad moderately sloping spur ridges run off the main ridges with relatively sharply incised gullies separating adjacent spur ridges. Steep slopes occur at the end of some main ridges. Depositional surfaces are quite common in gullies. The midslope gully-bottom sites sampled are examples of such surfaces, although neither has the deep A horizon (up to 1 metre) found in some gully-bottom profiles. The A horizon on some midslope spur ridges has been destroyed during clear-felling. Such sites were avoided during sampling. The main ridges have been eroded during pedogenesis and commonly have only a weakly developed A horizon.

EXPERIMENTAL METHODS

Sampling

Eight sites were chosen for sampling to cover the observed growth variations on four of the main topographic units present within the Mapua hill soils. All of the sites were within 3 km of Harakeke which is 12 km south of Motueka. The sampled units were steepland (sites M1 and M2), midslope spur ridges (M5, M6), midslope gully bottoms (M3, M4), and main eroded ridge tops (M7, M8). The steepland sites were in Tasman Forest (M1) and at Braeburn (M2) in stands of 10-year-old second rotation regenerated and 8-year-old planted first rotation radiata pine respectively. The midslope spur ridge and gully bottom sites and the main ridge sites (M3 to M8) were situated in Compartment 6 of Tasman Forest in a stand of 14-year-old second rotation regenerated radiata pine with stocking at 700 stems per hectare.

Soil samples were collected as subsamples of the soil excavated by genetic horizons from within a 0.5 m² pit. Only data from the A₁ horizon are included in this paper as this was the zone of maximum rooting observed in the Mapua hill soils. Chemical data and morphological descriptions of the complete profiles are given elsewhere (Adams, 1970).

The eight co-dominant trees closest to each soil pit were felled, half in May 1968, and the remainder in May 1969. Stocking rates remained constant at all sites between the two sampling dates. The height and diameter at breast height (d.b.h.) of each tree were measured. All branches from the top whorl of each tree were collected. These were placed in calico bags prior to drying at 80°C within 48 hours of collection. All needles from all branches were ground and stored in polypropylene bottles.

Foliar Analyses

Samples were dry-ashed following Piper (1942) except that the insoluble silica residue was discarded. The extracts were used for the determination of phosphorus (P) using metavanado-molybdate (Kitson & Mellon, 1944) and aluminium (Al) using ferron (Belyayeva, 1966). Calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), and zinc (Zn) were determined by atomic absorption spectrophotometry and potassium (K) by emission flame photometry. A semi-micro Kjeldahl method using a selenium catalyst (Metson, 1956) was used to determine nitrogen (N). Boron was determined colorimetrically using carmine/concentrated sulphuric acid on a separately ashed sample (Hatcher & Wilcox, 1950).

Soil Analyses

Soil analyses other than total elements were done on air-dried material passing a 2-mm

sieve. Total elements were determined on soil ground to pass a 250- μm sieve. Exchangeable Ca, Mg, K and Al were determined after leaching with neutral 1 M ammonium acetate by the chemical analysis methods outlined in the previous section. Total Ca, Mg, K and Al were similarly determined on sodium carbonate fusion extracts. Total Fe and P were determined colorimetrically on the fusion extracts using o-phenanthroline and the method of Dickman & Bray (1940) respectively.

“Available” phosphate levels were determined by the Bray No. 2 method (Bray & Kurtz, 1945) and the Olsen method (Olsen *et al.*, 1954). The sum of the NH_4F , 1st NaOH, and HCl extractions in the inorganic P fractionation of Williams *et al.* (1967) represents non-occluded P.

Easily-reducible Mn was determined by atomic absorption after extracting with neutral 1 M ammonium acetate containing 0.2% hydroquinone (Sherman *et al.*, 1942).

Hot-water-soluble B was determined by a modified form of the method of Gupta (1967). Twenty-five grams of soil were boiled with 50 ml water for 5 mins. After centrifuging, an aliquot was removed, 2 ml of saturated $\text{Ca}(\text{OH})_2$ was added and the solution evaporated to dryness. After igniting to remove organic matter the crucible was cooled and the residue dissolved in 2 ml of 2 M HCl. Boron was determined in this extract as for foliar samples.

Statistical Analysis

Simple correlation coefficients were calculated between soil and foliar nutrient levels. Foliar data from individual trees were correlated with the corresponding soil data (hence obtaining an increase in the error degrees of freedom) as well as correlating average foliar nutrient levels with the corresponding soil nutrient levels.

Stepwise multiple linear regression analysis was used to investigate the relationships between tree size index (TSI) and foliar nutrient levels. The analysis was performed using a computer programme with procedures for the stepwise addition of terms in order of decreasing significance and which provided for each step the multiple correlation coefficient, a goodness-of-fit term, the estimated standard error of the calculated dependent variable, and t-test values for each coefficient. The programme also provided simple correlation coefficients between tree size index and foliar nutrient levels. The multiple regression analysis used data from the M3 to M8 sites only.

RESULTS AND DISCUSSION

Relationship Between Tree Size Index and Topography

Although volume tables for the Nelson region are available (Duff & Burstall, 1955), the volume of a significant number of trees had to be extrapolated from outside the range of the basic data in the tables. Because it was felt that this might lead to errors in the statistical analysis of the results, it was decided to measure relative productivity between trees by means of a tree size index (TSI) defined as the product of (d.b.h.)² and tree height. Subsequent correlation analysis showed a very highly significant correlation ($r = 0.999$; $P < 0.001$) between total stem volume above ground (Duff & Burstall, 1955) and TSI suggesting that TSI provides a meaningful estimate of wood volume for individual trees.

The range and means of tree height, d.b.h., and TSI of radiata pine on three of the four sampled topographic units are presented in Table 1. Due to the younger age-classes

of the sampled steepland trees no comparable calculations of TSI were made. However, growth at both sites appeared good with no visual evidence of nutrient deficiencies.

The relationship of TSI to topography is evident in Table 1 with considerably better tree growth in gully bottoms than on ridges. The relatively good growth at M7 is considered to be due to the site being on a minor depositional surface just below the main ridge.

Trees at the M5, M6, M7 and M8 sites show the fine branching and thinly-needled crowns characteristic of nitrogen deficiency which has been described in this area (Stone & Will, 1965a; Appleton & Slow, 1966).

TABLE 1 - Variation in tree height, trunk diameter, and tree size index with topography.

Site		Tree height (ht)	Trunk diameter (d.b.h.)	Index of tree size (d.b.h.) ² x ht m ³	Tree age years	Topographic unit
		m	cm			
M1		n.d.	n.d.	n.d.	10	Steepland
M2		n.d.	n.d.	n.d.	8	Steepland
M3	range mean	21.4-25.3 22.9	25-43 31	1.35-4.44 2.20	14	Midslope gully bottom
M4	range mean	20.7-27.8 23.7	21-43 32	0.95-5.11 2.43	14	Midslope gully bottom
M5	range mean	12.5-20.4 15.8	10-22 16	0.12-0.97 0.40	14	Midslope spur ridge top
M6	range mean	13.4-21.4 16.0	8-20 14	0.09-0.88 0.31	14	Midslope spur ridge top
M7	range mean	15.3-21.4 17.9	11-27 22	0.20-1.58 0.87	14	Main eroded ridge top, some deposition
M8	range mean	10.7-17.1 14.5	9-20 16	0.09-0.70 0.37	14	Main eroded ridge top

n.d. = not determined

Foliar Nutrient Levels

The means of foliar nutrient levels for the elements N, P, K, Ca, Mg, Al, Mn, Fe, B, and Zn in the sampled trees at each site are presented in Table 2.

Comparison of mean foliar nutrient levels with mean TSI at each site (Table 1) shows that, for the sites where TSI was measured, poor growth is generally associated with lower foliar levels of N and P, higher levels of Ca and Mn, and slightly higher levels of foliar Al.

Critical foliar levels for radiata pine needles in New Zealand, below which growth is usually restricted, are 1.5-1.6% for N, 0.11% for P, 0.4% for K, 0.06-0.8% for Mg, and 8 ppm for B (Will, 1966; Stone & Will, 1965b). These levels have been derived from samples taken from a standard mid-crown position, rather than from the top whorl as in this study.

Table 2 - Mean foliar nutrient levels in radiata pine, Tasman Forest

Site		N	P	K	Ca	Mg	Al	Mn	Fe	B	Zn
		%	%	%	%	%	ppm	ppm	ppm	ppm	ppm
M1	mean	1.55	0.18	0.90	0.145	0.155	615	340	90	10	40
M2	mean	1.75	0.16	1.25	0.160	0.130	910	400	90	13	55
M3	mean	1.70	0.27	1.30	0.100	0.200	690	360	100	17	65
M4	mean	1.60	0.21	1.20	0.105	0.125	710	370	105	18	55
M5	mean	1.20	0.13	1.25	0.185	0.150	860	535	90	13	55
M6	mean	1.30	0.14	1.40	0.165	0.135	885	610	90	17	55
M7	mean	1.45	0.14	1.20	0.125	0.145	910	630	90	15	50
M8	mean	1.40	0.13	1.30	0.185	0.150	870	915	90	17	55

Comparison of results in Table 2 with these levels indicates the likelihood of N deficiency on both main and midslope spur ridges while foliar N in gully bottom and steep land trees is close to the critical level. This supports earlier studies in Tasman Forest which found N to be the limiting element to satisfactory tree growth on hard ridge sites (Stone & Will, 1965a; Appleton & Slow, 1966). Mean foliar N:P ratios calculated from Table 2 range from 6.2 at the M3 site to 10.9 at the M8 site. All values are within the usual range (5-16) for radiata pine (Raupach, 1967).

Mean foliar P levels at all sites are above critical values but are generally lower in trees showing poor growth. No foliar Al levels are known to have been published for New Zealand forests but levels in this study seem rather high when compared with published Australian figures (Humphreys, 1964). The A horizons of all soils in this study are extremely acid (Table 3). Availability of soluble Al is greatly increased in such conditions (Black, 1968). Humphreys and Truman (1964) have suggested that high Al availability in the soil will require radiata pine to take up greater amounts of P to attain the same growth as one grown in the absence of, or at low concentrations of Al. They suggested that this could have important implications for forestry practice on low-phosphate soils.

TABLE 3 - Chemical analyses of A horizons of sampled Mapua hill soils

Site	A horizon depth cm	pH	Organic Matter			Phosphorus				Cation Exchange				Easily re- ducible		Hot- water soluble
			Organic C %	Total N %	C/N	Total ppm	non-occluded ppm	Bray 2 ppm	Olsen ppm	CEC me. %	Ca me. %	Mg me. %	K me. %	Al ppm	Mn ppm	B ppm
M1	15	4.6	1.79	0.085	21	185	30	5.4	4.6	10.1	0.99	0.67	0.21	58	10	0.15
M2	20	4.4	2.11	0.091	23	144	23	4.0	4.2	11.3	1.41	1.13	0.21	49	19	0.29
M3	20	4.4	1.51	0.049	31	100	32	7.3	4.3	8.8	0.35	0.34	0.09	56	2.4	0.15
M4	14	3.9	1.73	0.058	30	115	34	5.1	4.3	8.8	0.54	0.40	0.10	67	0.6	0.10
M5	19	4.4	1.21	0.047	26	123	20	3.7	3.3	10.6	0.77	0.54	0.14	91	8.4	0.08
M6	16	4.1	1.80	0.051	35	98	16	3.9	3.7	9.4	0.47	0.40	0.12	78	0.0	0.15
M7	15	4.2	1.19	0.038	31	81	13	4.7	2.7	6.2	0.44	0.28	0.07	71	18	0.00
M8	15	4.4	1.47	0.040	37	83	13	3.4	2.5	6.7	0.55	0.41	0.08	60	23	0.01

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% = per 100 g oven-dry soil

Fig. 1 shows the relationship between mean foliar P : Al ratios and mean foliar P levels at the eight sampling sites. It is considered that a situation similar to that described by Humphreys and Truman may be present in the soils being discussed here. Comparison of Bray No. 2 and Olsen soil P levels at the four ridge sites (M5 to M8 in Table 3) with those of Ballard (1970) suggests that soil P may be deficient. Although foliar P levels at the ridge sites exceed the published critical level of 0.11% they almost certainly indicate some degree of P deficiency. At gully sites the rather higher soil P levels presumably provide a sufficient supply for satisfactory tree nutrition despite the quite high levels of available Al also present at these sites.

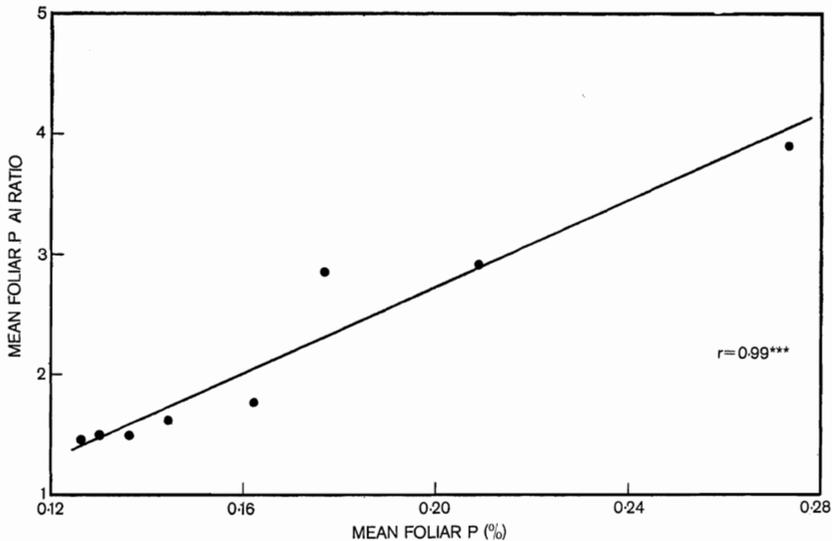


FIG. 1—Relationship between mean foliar P : Al ratios and mean foliar P levels from eight sites on Mapua hill soils (*** $P < 0.001$)

Mean foliar Mn levels are quite high at all sites but more particularly so in radiata pine at the four ridge sites. These observed high levels probably result from increased Mn uptake on these strongly acid soils (Table 3). Foliar Mn levels at the M8 site considerably exceed the critical toxic Mn foliar level of 700 ppm suggested by Lanuza (1966) for radiata pine. This level was established from pot and culture trials but has yet to be confirmed in mature forests. The value of 700 ppm, although rather low compared with that of some pasture species and in view of the acid soils on which radiata pine appears to thrive, agrees well with data in this study. Thus it is interesting to consider the relationship between TSI and foliar Mn levels shown in Fig. 2. If trees of less than one size-unit (1 m^3) are classed as poor trees, the mean height of the 29 poor trees is 15.7 m and the mean d.b.h. 15.7 cm compared with 22.7 m and 30.7 cm in the 19 good trees. Sixteen of the poor trees have foliar Mn levels greater than 700 ppm and 26 have levels greater than 450 ppm. Only six of the good trees have foliar Mn levels in the latter category while none contains above 700 ppm. The suggested toxic foliar Mn level of 700 ppm (Lanuza, 1966) therefore seems to broadly apply within

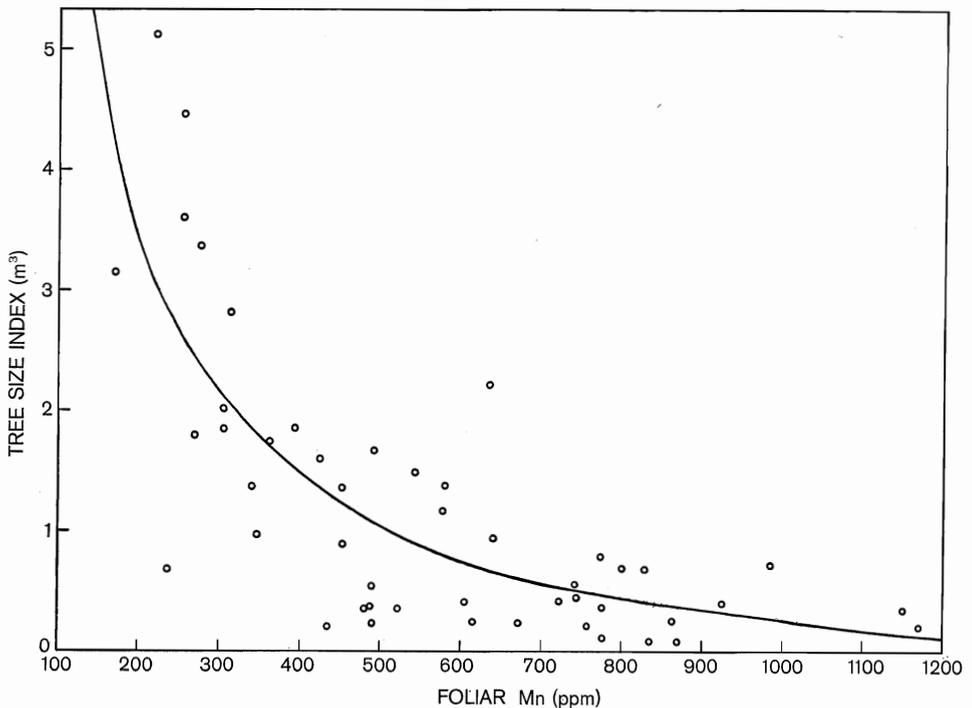


FIG. 2—Relationship between tree size index and foliar Mn in radiata pine in Tasman Forest

the area studied. Further work is required, however, to establish a more definite toxic critical foliar level for Mn in stands of radiata pine.

The association of low foliar P levels with possibly toxic Mn levels suggests the possibility of a P/Mn interaction (Walsh & Neenan, 1956). Regardless of whether or not such an interaction occurs, the extremely acid soils in Tasman Forest suggest that addition of phosphate alone is unlikely to cause a significant lowering in Mn uptake unless by a dilution effect. Conversely the deficient levels of soil P on the poor sites and the only marginally satisfactory levels on the good sites suggests that alleviation of Mn toxicity is unlikely to lead to a significant improvement in P nutrition.

Soils

Details of chemical analyses of the sampled A horizons are given in Table 3. The low levels of all plant nutrients are immediately apparent. All soils are extremely acid. Total N at all sites is very low while the high C/N ratios confirm the slow breakdown of organic matter reported by Noonan (1969) in these soils. Cation exchange capacity is low while levels of exchangeable cations are low or very low in all samples. Total and available P levels are very low.

Comparison with Table 1 shows that poor tree growth is generally associated with lower total and available P (as measured by three methods) and slightly lower total N. Exchangeable Al is slightly higher at those sites showing poor growth.

Simple correlation coefficients between corresponding soil and foliar variables are

presented in Table 4. In situations where trees are under nutrient stress, a close correlation between soil nutrient levels and foliar levels might be expected, provided that the measure of soil nutrient levels is one that relates to tree uptake. Correlation analysis between soil nutrient levels and foliar nutrient levels from individual trees shows that a very highly significant correlation exists between all three measures of soil P used and foliar P levels, with Bray No. 2 P showing the highest correlation coefficient and Olsen P the lowest correlation coefficient. When mean site foliar nutrient levels are considered, Bray No. 2 P remains significantly correlated with foliar P at the 0.1% level while non-occluded P and Olsen P are significantly correlated at the 1% and 10% significance levels respectively.

TABLE 4 - Results of simple correlation analysis
between soil and foliar nutrient levels

Soil variable	Foliar variable	Correlation coefficient	
		Individual trees	Plot means
Total nitrogen	Nitrogen	0.385**	0.612*
Non-occluded phosphorus	Phosphorus	0.626***	0.864**
Bray No. 2 phosphorus	Phosphorus	0.703***	0.944***
Olsen phosphorus	Phosphorus	0.516***	0.715*
Exchangeable calcium	Calcium	0.147	0.392
Total calcium	Calcium	0.040	0.187
Exchangeable magnesium	Magnesium	-0.135	-0.358
Total magnesium	Magnesium	-0.136	0.332
Exchangeable potassium	Potassium	-0.222	0.032
Total potassium	Potassium	-0.095	0.025
Exchangeable aluminium	Aluminium	0.207	0.183
Total aluminium	Aluminium	-0.035	0.333
Total iron	Iron	0.011	0.123
Easily-reducible manganese	Manganese	0.385**	0.575
Hot-water-soluble boron	Boron	-0.113	-0.309

*** P < 0.001

** P < 0.01

* P < 0.10

The significant correlations between foliar P and all measures of soil P confirm earlier findings on soil from granite in Nelson that each of these phosphate extraction methods provides a satisfactory indication of tree-available P (Adams, 1970). Levels of 5 ppm and 3.5 ppm for Bray No. 2 and Olsen extractable P respectively have been shown to be necessary for satisfactory growth of radiata pine in Auckland and Nelson forests (Ballard, 1970; Adams, 1970). Comparison of these values with those for Bray No. 2 P and Olsen P levels in Table 3 shows that, while differences between sites are not particularly marked, values for both extraction methods are generally above the suggested threshold values at the M1-M4 sites and below the threshold values at the M5-M8 sites. This pattern correlates closely with the observed tree growth at these sites (Table 1). When considered together with foliar nutrient levels the soil data strongly suggest the presence of a phosphate deficiency in trees at ridge sites.

Total soil N might be expected to give a good indication of N availability for tree growth over a limited range of soil type and climate. Data in Table 4 show that total soil N is significantly correlated with foliar N when both individual tree foliar levels or mean site foliar levels are used. Consideration of the foliar and soil data therefore suggests that nitrogen deficiency may be a factor in growth differences in trees in Tasman Forest. The highly significant correlation between easily-reducible Mn and foliar Mn when individual tree nutrient levels are considered becomes non-significant when mean site foliar nutrient levels are used. The soil data are therefore of only limited use in assessing the possibility of Mn toxicity being a factor in the observed growth differences. This is not unexpected as suitable extractants for soil Mn available to trees have not been studied up till now.

Statistical Analyses

Results of simple linear correlation analysis between TSI and foliar nutrient levels are given in Table 5. Six of the ten foliar nutrients measured are significantly correlated with TSI with foliar P, Ca, and Mn being correlated with TSI at the 0.1% level, foliar N and Fe being correlated at the 1% level, and foliar Al being correlated at the 5% level. The highest correlation is with foliar P (0.703) followed by Mn (-0.663), Ca (-0.615), Fe (0.394), N (0.378), and Al (-0.352).

Relationships between tree growth and foliar P, Mn, and N have been discussed earlier. The very highly significant negative correlation of TSI with foliar Ca levels is not considered to be due to a direct causal relationship between TSI and site calcium nutrition but rather to a dilution effect from the differences in tree size. Thus a relatively constant quantity of Ca in all trees would give a higher concentration in poor trees than in good trees. Such a dilution effect is considered to be a consequence of the significantly better phosphorus nutrition at the gully sites. This conclusion is supported by highly significant correlations between soil Bray No. 2 P levels and mean foliar Ca levels ($r = 0.867$, $P < 0.01$), and between mean foliar P levels and mean foliar Ca levels ($r = 0.812$, $P < 0.01$).

The significant negative correlation between TSI and foliar Al levels ($r = 0.352$, $P < 0.05$) tends to confirm the presence of an acidity factor. This seems likely to be present as a toxicity of Mn or Al rather than as a Ca deficiency.

Multiple regression analysis may be used either to develop the "best" equation to predict the maximum value of the dependent variable in terms of a number of independent variables, or for the mathematical representation of a situation which may suggest

TABLE 5 - Simple correlation coefficients between and within tree size index and foliar nutrient levels.

	Tree Size	N	P	K	Ca	Mg	Al	Fe	Zn	Mn	B
Tree size	1.000										
N	0.378**	1.000									
P	0.703***	0.420**	1.000								
K	0.125	-0.226	0.241	1.000							
Ca	-0.615***	-0.221	-0.480***	-0.106	1.000						
Mg	-0.044	0.408**	0.078	-0.227	0.357*	1.000					
Al	-0.352*	-0.128	-0.180	0.147	0.368*	-0.004	1.000				
Fe	0.394**	-0.031	0.380**	0.286	-0.204	0.015	0.285	1.000			
Zn	0.140	0.308*	0.324*	0.250	0.225	0.457**	0.262	0.182	1.000		
Mn	-0.663***	-0.151	-0.529***	-0.140	0.654***	0.150	0.287*	-0.343*	-0.082	1.000	
B	0.103	0.201	0.197	-0.040	-0.025	0.333*	0.059	0.236	0.122	0.122	1.000

*** P < 0.001

** P < 0.01

* P < 0.05

possible causal relationships between the dependent variable and independent variables (Yarranton, 1971). The selection of variables is extremely important in the latter case and hence the "best" mathematical representation may not necessarily be identical to the "best" predictive equation. The development of a mathematical representation of the relationship between TSI and foliar nutrient levels was of interest in this study with the aim of cross-correlating the nutritional evidence, thus investigating any interactions which might be present. This allows interpretation to proceed further than is possible with data obtained from soil and foliar analyses, and pilot field trials involving a necessarily limited series of treatments. A basic assumption underlying the analysis was that foliar nutrient levels and TSI both reflect site quality and hence are closely inter-related.

The "best" mathematical representation obtained was that shown in equation 1. Dependent variables were placed in order of decreasing significance on entry.

$$\text{TSI} = \frac{635^{***}}{\text{Mn}} + 0.000511 \text{ P}^{**} + 0.0000852 \text{ N}^* - 2.299 \quad (1)$$

$r = 0.859$
 $*** \quad \text{P} < 0.001$
 $** \quad \text{P} < 0.01$
 $* \quad \text{P} < 0.05$

This equation explains nearly 74% of the variation in TSI and suggests that the main factors affecting TSI are a high uptake of Mn and deficiencies of P and N. This provides support for the conclusions reached earlier from the considerations of foliar and soil nutrient levels and soil-foliage correlations.

In equation 1 foliar P is inserted at a t-test value considerably higher than that for foliar N suggesting that P is of more importance than N to tree nutrition in Tasman Forest. This conflicts with earlier conclusions based on field trials. These have generally shown that additions of P alone produce no response whereas N alone or N plus P produce significant increases in tree growth (Stone & Will, 1965a; Appleton & Slow, 1966). A close relationship between the two elements is suggested in this study by the highly significant correlation ($r = 0.420$, $\text{P} < 0.01$) between foliar P and foliar N levels.

Noonan (1969) has concluded that there is sufficient N present in the soils of Tasman Forest to allow decomposition of residues after clear-felling. However, mineralisation is so slow that insufficient nutrients become available to supply the needs of dense regeneration. Data in this study suggest that this slow mineralisation may be a consequence of the acidity of the system, a deficiency of P, or a combination of these two factors. No studies have investigated the presence of free-living, N-fixing organisms in Tasman Forest soils. If present their effectiveness may be severely limited by soil acidity and P deficiency.

Additions of P plus lime or perhaps P alone might have beneficial effects on the apparently excessive Mn uptake, the rate of mineralisation of residues, and the activity of any free-living, N-fixing organisms. Such additions could eventually lead to an improvement in the nitrogen balance of the system to a point where no further additions of N would be required.

CONCLUSIONS

Mapua hill soils contain very low contents of most plant nutrients but within the soil mapping unit deposition surfaces in gullies appear to be rather more fertile than

eroded surfaces on ridges. Differences in site fertility between the two landforms are not large but they do seem to be important in tree nutrition. The data of Kingston (1968) also suggest that better summer soil moisture conditions in gullies may play an important part in maintaining tree growth for longer periods than on ridge sites.

Insufficient analyses are presented to allow any categorisation of limiting soil chemical levels other than to confirm soil P levels necessary for good growth (Ballard, 1970). Further investigations are needed before limiting soil properties can be defined to the point where potential site quality can be accurately predicted on marginal sites.

A combination of foliar and soil analyses, soil-foliage correlation analysis, and stepwise linear multiple regression analysis has shown that the main nutritional factors affecting radiata pine growth on hard sites such as ridges in Mapua hill soils in Tasman Forest are deficiencies of phosphorus and nitrogen together with an acidity factor which is present as manganese toxicity. It appears possible from the data that the nitrogen deficiency is more a problem of availability due to the strongly acid environment and low phosphate levels reducing the rate of microbial release of nitrogen from soil organic matter than a problem of direct nitrogen deficiency. If this is so attempts should be made to improve the rate of nitrogen mineralisation by additions of phosphate and lime. This might be expected to improve the nitrogen balance of the system to a point where further additions of nitrogen fertilisers would be unnecessary.

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