EARTH SCIENCE JOURNAL Vol. 4, No. 1, 1970

AN APPRAISAL OF NUTRIENT SUPPLIES AVAILABLE FOR TREE GROWTH IN A PUMICE SOIL

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Abstract

Chemical analyses have confirmed and explained the results of an earlier pot trial in which the availability of major nutrients in six pumice ash layers of Kaingaroa silty sand was assessed by the growth of radiata pine seedlings.

Almost all of the tree-available P is found in the present topsoil: the quantities of P that occur in two buried soils (Waimihia and Rotoma ashes) are almost entirely in the form of organic P which is apparently very resistant to breakdown due to complexing with allophane. The N in these layers is similarly unavailable.

The mineral layers, about 4 ft in thickness (Taupo pumice and lapilli), which lie between the present topsoil and the uppermost buried soil, are very low in total N and P and exchangeable Mg, but relatively high in exchangeable K. Only the lower buried soil contains a reasonable quantity of exchangeable Mg and has a Mg : K ratio in favour of Mg.

INTRODUCTION

It has been shown that in the various layers of Kaingaroa silty sand profile in the central region of Kaingaroa Forest there is adequate moisture storage capacity for sustained tree growth (Will and Stone, 1967). Will and Knight (1968) described a pot study in which the nutritional potential of each of the six main component layers was examined by intensive cropping with *Pinus radiata* seedlings.

This paper describes the soil chemistry of the layers, seeks to relate it to the nutritional differences found in the pot study and endeavours to probe into some aspects which might affect the longer term potential of this pumice soil for tree nutrition.

Will (1964) reported analyses for Ca, K and P (total and 'available') in the surface three feet of soil from seven sites, some miles apart in central Kaingaroa Forest; these analyses showed little variation from site to site. Healy *et al.* (1964) and Pullar (1968) have shown that the soil profiles at widely separated points in Kaingaroa Forest generally comprise the same succession of rhyolitic ash members. It can therefore be reasoned, with some confidence, that the results of both the pot trial and the analyses reported here are representative of a large area of the forest. The layers which make up the profile have been identified by Pullar (1968). The chronology and stratigraphy of the bedded ash members which these layers comprise have also been described (Healy *et al.*, 1964).

Briefly, the ash showers were the products of a series of intermittent volcanic eruptions of varying intensities, which took place from a number of vents in the Taupo and Okataina volcanic centres, mostly during the Holocene. The upper five feet of the profile are less than 2000 years old (Healy *et al.*, 1964) while the age of the deepest of the layers examined has been estimated to be about 11,000 years.

The typical assemblage of minerals in rhyolitic ash has been described (Fieldes and Weatherhead, 1966) and consists of approximately 60% acid intermediate glass, 30% acid feldspar tending towards andesine, 3-6% pyroxenes and amphiboles, together with small amounts of other accessory minerals including apatite.

The clay fraction of soils derived from rhyolitic ash has been recognised as predominantly allophane (Birrell and Fieldes, 1952; Fieldes and Williamson, 1955); the properties peculiar to this form of 'amorphous' clay are well recorded (Dixon, 1954; Fieldes and Perrott, 1966).

Earlier estimates of 'available' soil phosphorus in the surface three feet (Will, 1964) were based on citric acid extracts. Where the phosphorus is 'fixed' in the form of iron or aluminium phosphates, or where organic content is high this method tends to give an exaggerated index of availability (Metson, 1956). Intensive cropping of the layers by radiata pine seedlings in the pot study resulted in a lower uptake of phosphorus than might have been expected from this index of availability, and this called for further examination of the soil phosphorus content and its availability.

Tiller (1957) has shown that pines are able to enrich the topsoil with nutrients derived from parts of the profile many feet below the soil surface. As mature exotic pines in Kaingaroa Forest commonly root to depths of up to 10 feet, a knowledge of the distribution of nutrients throughout the entire rooting zone is of fundamental importance to gauge the potential of the soil for future tree crops.

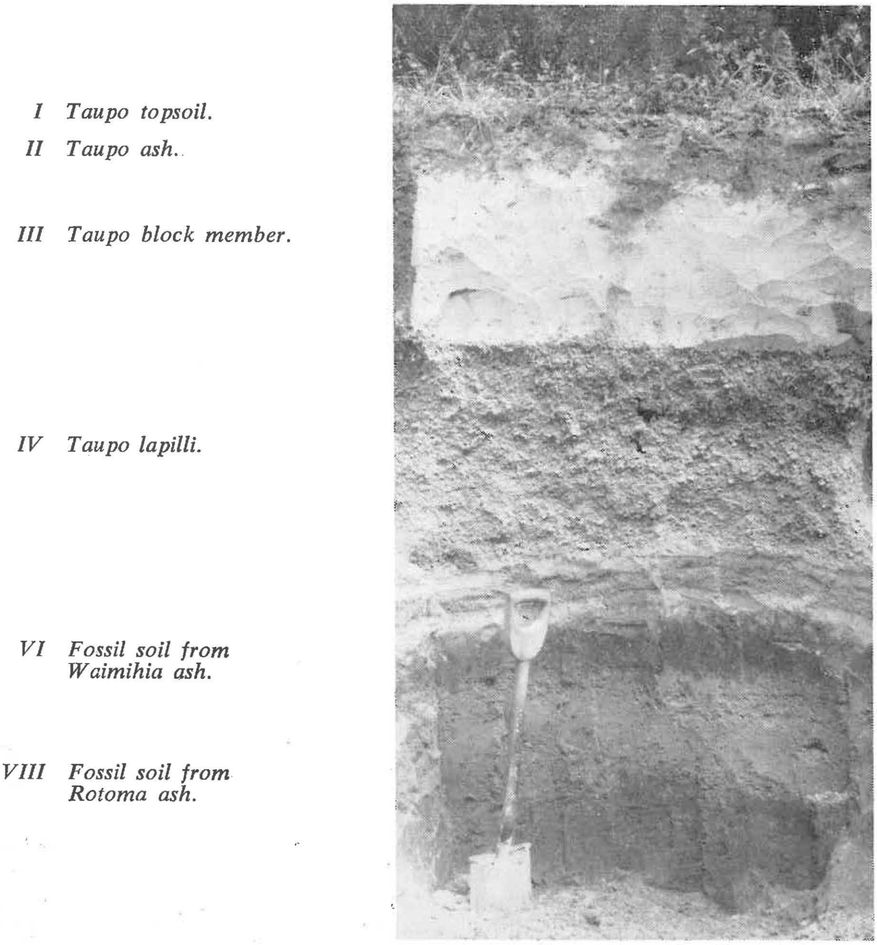

Figure 1 : Soil profile central Kaingaroa Forest near Wairapukao.

The two buried, former surface soils now at depths of 5.5 and 7.5 feet are of particular interest in this respect, since the pot trial showed that they contain comparatively useful amounts of available magnesium—a nutrient in short supply in other parts of the profile. Fine feeding roots of trees do not occur to any extent in the thin layers designated V and VII in the soil moisture study (Will and Stone, 1967). As these layers are therefore of doubtful importance to tree nutrition they have not been included for consideration here.

The site index (expected mean top height at age 20 years) for radiata pine in the compartment sampled is *ca.* 95; the site quality is currently described as IIa-IIb (D. J. Mead—unpublished data).

METHODS

Soil samples were collected from the six principal layers in which tree roots occur in Compartment 69, Kaingaroa Forest. The soil profile is shown in Fig. 1 and the layers studied are designated I, II, III, IV, VI and VIII in accord with the numbering sequence used in a study of moisture properties (Will and Stone, 1967). Layers V and VII were not included in this study.

Twelve topsoil samples were taken, after removal of the litter, from areas undisturbed by past logging operations. These samples were bulked to give a composite sample. The remaining five layers were sampled from a freshly exposed surface on the side of a cutting made during the construction of a device to collect drainage water below the rooting zone.

RESULTS AND DISCUSSION

The results of the soil analyses of the six principal layers of bedded pumice ash which lie within the tree rooting zone in Compartment 69, Kaingaroa Forest, are set out in Table 1.

In considering these results in relation to tree nutrition caution must be exercised, since over the relatively long life of a tree crop, sources other than those at present available may contribute substantially to the nutrient requirements of the trees. Within the soil profile itself weathering of primary and accessory minerals results in slow release of nutrients. Cyclic processes involving the return of nutrients in litter and rainfall also significantly influence the nutrient status of the soil (Will, 1959). Another important phenomenon is the microbial fixation of gaseous nitrogen, which commonly results in nitrogen accretion within the soils of coniferous forests (Richards, 1964). Soil fertility ratings for agricultural soils based on chemical tests are not applicable to forest soils since agricultural crops grown for foodstuffs place greater short term nutritional demands on the soil than the "timber" crops of forestry. Most exotic pines are, in fact, dual organisms since the unsuberized part of their root system is generally covered with a sheath of ectotrophic mycorrhiza; these mycorrhizal root systems are more efficient at obtaining mineral nutrients from infertile soils than are the roots of non-mycorrhizal plants (Hatch, 1937). The extent to which mature trees with well-developed mycorrhizal roots are able to exploit 'fixed' soil phosphorus is largely a matter for conjecture at present.

Variability of nutrient content from layer to layer

Table 1 shows that the individual layers differ considerably in their content of available nutrients as indicated by content of exchangeable calcium, potassium and magnesium, Truog phosphorus and total nitrogen. The layers can be broadly distinguished into those which contain organic matter in some quantity, i.e. the topsoil (layer I) and both 'fossil' topsoils (layers VI and VIII), and those which are practically devoid of humus or organic matter, consisting almost entirely of pumice ash (layers II and III), or of lapilli (layer IV). The humified layers, as

Table 1 Results of chemical analyses of the six principal layers of soil within the tree-rooting zone in compartment 69, Kaingaroa Forest.

Layer designation	I	II	III	IV	VI	VIII
Description	Topsoil: silty sand	Silty sand	Sand	Lapilli	Fossil topsoil: silty sand	Fossil topsoil: silty sand
Depth below surface (ft)	0.1 – 0.6	1.0 – 2.0	2.0 – 3.0	3.0 – 5.0	5.5 – 6.5	7.5 – 8.5
pH in water 1 : 2.5	5.1	5.6	5.7	6.1	6.2	6.1
Indices of P availability mg % P:						
Olsen	1.5	0.2	0.3	0.4	0.3	0.2
Bray No. 2	2.2	0.5	0.5	0.6	0.2	0.1
Truog	2.0	0.2	0.3	0.3	0.2	0.1
Citric acid soluble	12	3	1	7	2	2
N H_2SO_4 soluble (P_1)	13	9	7	14	3	2
Total P : *N* H_2SO_4 extraction after ignition (P_2)	40	18	12	14	17	22
HClO$_4$ extraction	41	14	9	7	16	21
Organic P ($P_2 - P_1$) mg % P	27	9	5	0	14	20
P retention (%)	51	40	24	0	38	68
Organic carbon (%)	4.2	0.5	0.3	0.1	0.8	1.6
Total organic matter (org. C × 1.724) (%)	7.2	0.9	0.5	0.2	1.2	2.8
Total N (%)	0.23	0.04	0.02	0.01	0.06	0.09
C/N ratio	18	12			13	18
Cation exchange capacity (me%)	13.4	5.6	4.2	2.3	7.4	14.0
Exchangeable cations (me%)						
Calcium	1.2	0.4	0.3	0.4	1.2	2.8
Magnesium	0.38	0.06	0.06	0.02	0.20	0.55
Potassium	0.68	0.80	0.91	0.91	0.79	0.18
Sodium	0.10	0.87	0.76	0.58	0.35	0.10
Sum of exchangeable cations (me%)	2.36	2.13	2.03	1.91	2.54	3.63
Base saturation (%)	16	39	50	78	35	25
Reserve K index (me%)	0.5	0.2	0.3	0.1	0.3	0.1

might be expected, have higher cation exchange capacities than the mineral layers. Within the tree rooting zone the exchangeable calcium and magnesium are both mainly concentrated in the humified layers while the exchangeable potassium is more liberally disposed in the mineral layers; there is a paucity of this nutrient in the deepest humified layer VIII.

The preponderance of total nitrogen and available (Truog) P within the rooting zone is concentrated in the topsoil; small amounts of total N occur in the buried 'fossil' topsoils but Truog P values for all five buried ash layers are very low.

Relationship of pot trial evaluation to soil analyses

The occurrence and intensity of the particular nutrient deficiencies which developed in pine seedlings grown in each of the six layers can be directly related to the relative concentration of available forms of those nutrients which soil analyses showed to be present in the individual layers. While the two independent assessments of nutrient availability generally accord well, it would be misleading to place too fine an interpretion on the quantitative results of either the pot trial or soil analyses, since both methods of assessment are subject to limitations.

In glasshouse pot experiments the conditions under which the soils are held are artificial so that the availability of mineral nutrients is unavoidably altered to some degree through disturbance and effects on the microfauna/flora. Tissue analyses also require some interpretation, as factors distinct from actual supply of a particular nutrient in the soil can also influence plant composition—a low tissue value for a particular element may be due to ion interaction rather than to a poor soil supply of that nutrient. Reports of the depressive influence of a high soil content of exchangeable K on plant uptake of Mg are particularly prominent in the literature. In some instances certain combinations of nutrients applied during the pot trial to particular layers undoubtedly influenced the uptake of the nutrients not added—for example—four crops of pine seedlings grown in the topsoil treated with N, K extracted only 0.10g Mg and 0.15g P, whereas those grown in the untreated topsoil took up 0.15g Mg and 0.26g P; the final crop grown with the former treatment displayed pronounced visual P and Mg deficiency symptoms while the control crops were healthy in appearance.

Since the particular fraction removed from the soil by the arbitrary soil extractants used in laboratory assessments of nutrient availability can only approximate that taken up by actively growing plants, the results of such analyses also require 'interpretation.'

It is more prudent for these reasons to disregard the more subtle, marginal differences in nutrient availability which one or other method shows and to consider only the more meaningful grosser differences from layer to layer which are indicated by both methods. When considered in this way the results of both pot trial and soil analyses are, for the most part, compatible and the conclusions drawn from both are largely analogous. The synopsis of results in Table 2 illustrates how amounts of nutrients extracted by intensive cropping of the layers with radiata pine seedlings (Will and Knight, 1968) relate in order of magnitude to the amounts of 'available' nutrients based on results of soil analysis. For the purpose of comparison both sets of values are calculated on the basis of equal volumes of soil.

The values are recorded in **bold** figures where the supply of that nutrient in a particular layer remained adequate for healthy growth throughout the pot trial despite intensive cropping.

Total N rather than available fractions is reported in the table since the pot study gave indications of steady mineralisation: although seedling growth in the topsoil was limited by the supply of readily available N no significant increase in N stress occurred over the four years of the pot trial.

Table 2 Values for nutrients based on equal volumes of soil:
A. Content indicated by soil analysis
B. Amount extracted by intensive cropping with yearling radiata pine seedlings
lb/acre (thickness 12 inches)

Layer	N		P		K		Mg		Ca	
	A (Total)	B	A (Truog)	B	A (Exchangeable)	B	A (Exchangeable)	B	A (Exchangeable)	B
I	4502	572	39	33	520	198	90	55	462	153
II	826	144	4	2	647	457	15	31	149	91
III	467	*	7	2	832	378	17	14	117	69
IV	155	*	5	2	551	244	4	2	136	31
VI	1350	*	5	7	697	397	55	33	547	153
VIII	2299	29	3	Nil	180	81	171	55	1413	141

* Marked N deficiency symptoms were evident at an early stage in the first crop of seedlings grown without added N in these layers. Amounts of N extracted by these seedlings were extremely small but are not reported in this table since nutrients other than N were also limiting in these layers and may have resulted in depressed N uptake to some extent.

Distribution of nutrients within the tree rooting zone:

Under stands of mature radiata pines in Compartment 69, layer IV, which is composed of lapilli, is the only one of the six considered, in which fine feeding roots do not occur. This layer nevertheless is a major component of the soil profile and has been shown by the pot study (Will and Knight, 1968) to provide a good substrate for growth of pine seedlings when nutrients are not limiting. Root channelling through this layer may well promote more extensive exploitation by future tree crops.

Table 3 shows the relative amounts of P, K, Mg and Ca which soil analyses indicate the individual layers are potentially capable of contributing if additions such as may be derived from weathering processes, atmospheric precipitation and mineralisation of organic matter and, on the other hand, losses due to leaching are disregarded. Since there is no known chemical technique or reagent which is capable of selectively releasing the fraction of total soil N, which soil micro-organisms make available, this nutrient has been omitted from the table.

Table 3 Distribution of nutrients within the tree-rooting zone: an estimate based on weight per acre for each layer* and soil analyses data. (lb/acre)

	Average Thickness		Exchangeable		
Layer	in.	Truog P	K	Mg	Ca
I	6	20	260	45	231
II	12	4	647	15	149
III	12	7	832	17	117
IV	24	9	1103	8	273
VI	12	5	697	55	547
VIII	12	3	180	171	1413
Total		48	3719	311	2730

* Calculated from bulk densities by Will and Stone, 1967.

The following more detailed account of the distribution of the major plant nutrients within the tree rooting zone also includes discussion of some of the important factors which influence availability of particular nutrients:

Nitrogen

The total N determinations (Table 1) show that N supplies are not abundant in the profile as a whole. The greatest amount occurs in the topsoil (layer I); the two buried 'fossil' topsoils (layers VI and VIII) contain substantially less. The intervening layers (II, III and IV) contain only very little total nitrogen though a small amount does appear to have been carried down the profile into these layers. During the four years of the pot trial the supply of available nitrogen in the topsoil was maintained despite intensive cropping. The total nitrogen content fell from 0.23% to 0.14%. Although seedling growth was somewhat limited throughout the trial by the available N supplies no significant increase in N stress occurred in four consecutive crops. This was taken to indicate that, under glasshouse conditions, mineralisation of organic nitrogen in the topsoil occurred at a rate sufficient to steadily replace all or most of the nitrogen taken up by the seedlings. In this way a relatively constant though limited level of available nitrogen was maintained. On conclusion of the pot trial 61% of the total nitrogen originally present in the topsoil remained in the soil of the controls, while the amount extracted by the four crops accounted for only 16%. This suggests a substantial loss of nitrogen through denitrification.

Although the deepest humified layer (VIII) had the next best total nitrogen content (.09%) there was no indication that this constituted a source of available plant nitrogen since, even under glasshouse conditions, crops of seedlings grown in this layer failed to grow much beyond the cotyledon stage in size and gave every indication of acute nitrogen deficiency. This might indicate that the nitrogen present in this layer is protected and stabilised through absorption on clay colloids in the form of nitrogenous organic complexes. There can be little prospect that the small amount of total N present, which is buried to a depth of over seven feet, will be made available through microbiological activity. The same considerations apply to the upper buried topsoil, layer VI, which contains less total N. It appears therefore that the available resources of nitrogen are almost entirely confined to the topsoil.

The sufficiency of nitrogen resources for future rotations will depend on the efficiency of conversion of organic nitrogen to available forms and also the extent to which the existing resources of this nutrient are augmented from the atmosphere; losses due to leaching and denitrification have also to be considered.

The amount of nutrients added in atmospheric precipitation is currently being studied by collecting rainfall above the forest canopy; losses due to leaching are being examined by means of lysimeter collections. It can however be anticipated that such additions of nitrogen will not exceed 9lb/acre annually, which is the figure quoted by Richards (1964).

The pot study is a poor guide to the efficiency of conversion since the effect of the addition of fresh organic residues to the soil was virtually eliminated through removal of the litter layer at the time of sample collection. The addition of plant residues greatly influences the nitrogen resources of the soil humus since, by providing an energy source for a vigorous microbial population, they greatly accelerate the decomposition of soil organic matter (Bremner, 1951) and the mineralisation of organic forms of nitrogen. Thus, while the available nitrogen supply was limiting to dry matter production by seedlings grown in the topsoil during the pot trial, this would not necessarily be so in the field.

No reliable estimate of the rate of nitrogen fixation or accretion in this forest soil is available. However, Richards (1964), in reviewing current work on fixation of atmospheric nitrogen in coniferous forests, reported that an annual gain of 45lb per acre is frequently attained, even in the absence of nodulated species in the understorey. He also showed, by comparison of rates of accretion in afforested and non-afforested areas, that accretion of nitrogen is intimately associated with growth of trees.

Phosphorus

The levels of P extracted by Truog reagent, which are reported in Table 1, show that most of the readily available P content of the soil in the tree rooting zone occurs in the topsoil. This is confirmed by the results obtained with other extractants, namely Bray No. 2 and Olsen's sodium bicarbonate. Though tenfold the average of the other layers, this is a comparatively poor supply of readily available P.

Relatively substantial amounts of organic P occur in the topsoil and in both buried, humified layers (layers I, VI and VIII). The pine seedlings grown in the 'fossil' topsoils were not able to utilise any part of this form of P, exhibiting symptoms of acute P deficiency unless additional supplies of this nutrient were provided. However, there was some indication that seedlings grown in the topsoil had utilised a portion of the organic P in the course of the pot trial. This may have been due in part to the better initial root development resulting from the more favourable content of readily available P in the topsoil.

The amounts of P extracted by various methods from the topsoil prior to and after intensive cropping were as follows:

Table 4 Total, Truog and organic P analyses of topsoil (layer 1), before and after intensive cropping with radiata pine seedlings, showing the extent to which soil P was depleted by the seedlings (mg P per 100 g soil).

Extractant:	Truog reagent	N H_2SO_4			Na_2CO_3 (fusion)
		A Ignited soil	B Air dried soil	A-B Organic P	
Prior to cropping	2	40	13	27	44
After cropping	1	33	11	22	39

Will (1964) estimated that the amount of P removed from a site in thinning and subsequently clear felling a crop of radiata pine is of the order of 29lb/acre. From this it might be concluded that only two further thrifty crops could be supported by the soil, since the content of readily available (Truog) P corresponds to 48lb/acre. However over the several decades which pass during the life of a tree crop, a number of factors may invalidate such a conclusion: firstly, the enormous surface area exposed by volcanic ash results in active weathering throughout the whole profile and this may result in a steady if unspectacular release of available P from such minerals as apatite. Apatite has been reported (Fieldes and Weatherhead, 1966) among the accessory minerals of rhyolitic ash It is now generally recognised that the active absorption of nutrients by the roots themselves helps to promote weathering of soil minerals in contact with them.

Secondly, the decomposition of plant residues by soil microorganisms results in the production of various organic anions which are highly effective at mobilising 'fixed' iron and aluminium phosphate (Drake, 1964). Since the entire root systems of forest crops are generally left in the ground after logging, it seems likely that the products of their decomposition will include significant amounts of these chelating agents. During the life of trees, too, such compounds are continually produced in the rooting zone as decomposition by-products of the organic matter derived from the living roots when root hairs or wall are sloughed off, or when roots die.

Fieldes and Williamson (1955) have established that allophane is a major constituent of the clay fraction in the yellow-brown pumice soils derived from rhyolitic ash. The rapid test for allophane (Fieldes and Perrott, 1966) also gave positive results for this clay in each of the six layers considered here. This form of clay characteristically occurs in soils as a product of weathering of volcanic ash and its properties are such that it is capable of profoundly influencing the availability of nutrients in soils. This is particularly so with phosphorus since allophane strongly retains phosphate ions, possibly through co-ordination of oxygen atoms in such anions at tetrahedral aluminium sites (Fieldes, 1962). The phosphate held in this way is not readily available to plants. Allophane also associates with humus in surface soils forming very stable organo-mineral colloids; this impedes rapid mineralisation. Jackman (1964) has reported that in a similar soil type (Taupo silty sand) the organic P content of topsoil which had been ploughed down to six inches below the surface, had remained unaltered when examined after some 11 years under pasture. It seems reasonable to suppose that the organic P content of the 'fossil' topsoils, which has presumably persisted from the time of burial several thousand years ago, has endured as a result of association with allophane and subsequent isolation from microbiological activity.

Table 5 The effect of depletion of soil exchangeable K on seedling concentration and uptake of K.

Layer	Crop treatment	Soil content exch. K prior to cropping mg%	Seedling concn. K 1st crop %	Soil content exch. K after final crop mg%	Seedling concn. K final crop %	Net uptake of K by 4 crops g/pot
I	Control	27	0.60	3	0.17	0.6
II	+N, P, Mg	31	0.91	14	0.22	1.9
III	+N, P, Mg	36	0.73	n.d.	0.24	1.6
IV	+N, P, Mg	36	*	6	0.20	*
VI	+N, P	31	0.77	9	0.21	1.7
VIII	+N, P	7	0.41	0.1	0.11	0.3

* Sample not reported due to contamination.

Fieldes (1955) has concluded that the clays derived from rhyolitic ash pass through a definite sequence of forms with increasing age and he distinguishes three allophane phases. Thus the form of allophane occurring in the topsoil which is less than 1000 years old (Healy *et al.*, 1964) may differ from that in the much older, buried, humified layers. It has been noted that while radiata pine seedlings were apparently able to utilise a part of the organic P in the surface soil, this was not so with seedlings grown in the buried humified layers. The clay contents of these three layers are comparable, so this difference may be due in part to the nature of the allophane phase. The topsoil, however, contains significantly more organic P than the buried, former surface soils and it may simply be that, by virtue of the substantial quantity of litter which accumulates on the forest floor, a large proportion of the organic matter is free from association with the relatively small clay fraction and is subject to relatively rapid mineralisation.

Potassium

The profile as a whole contains a substantial amount of exchangeable K. The topsoil contains rather less than the four layers which lie in succession beneath it. Layer VIII is singularly low in content of both reserve and exchangeable K.

As the principal constituents of rhyolitic pumice ash are commonly acid feldspars and volcanic glasses (Fieldes and Weatherhead, 1966), the bulk of the mineral assemblage is in the form of distorted, linked tetraheda (feldspars) or random-structured aluminosilicates (glasses). A large part of the total K is inextricably enmeshed within the matrix of these minerals which are relatively slow weathering and, being of recent origin, are but little weathered. It follows therefore that release of K in an available form from these minerals is a much slower process than in the case of the layer-lattice minerals found in many other soil types.

In Table 5 it can be seen that the content of exchangeable K in each layer examined was markedly depleted by intensive cropping with pine seedlings. The table also shows the related fall in seedling concentration of this nutrient which occurred between the first and last crop.

The reserve K indices were determined on comparable samples before and after intensive cropping by extraction with boiling normal HNO_3 (Pratt, 1965); from Table 6 it can be seen that, of the layers examined, only layer VI was substantially altered as a result of intensive cropping. Layer VIII, which was singularly low in exchangeable K, shared the lowest index of reserve K with the layer IV lapilli.

Table 6. The effect of intensive cropping on release of K from non-exchangeable forms. *N* HNO_3 soluble potassium (mg %)

Layer	prior to cropping	after intensive cropping	Crop treatment
I	19	17, 18	Control
II	8	8	+ N, P, Mg
III	10	*	
IV	4	*	
VI	10	5	+ N, P
VIII	4	3	+ N, P

* Not determined.

Magnesium

The ash layers which lie between the topsoil and the two buried fossil topsoils are markedly deficient in exchangeable Mg. The topsoil itself is not rich in this nutrient and most of the exchangeable Mg within the rooting zone occurs in the 'fossil' topsoil (layer VIII) which lies some 7-8 feet below the surface of the soil.

Will (1966) has attributed the cause of spring chlorosis in the older foliage of young stands in central Kaingaroa to a magnesium deficiency resulting from peak demand for this nutrient during the spring flush of growth, coinciding with wilting point conditions in the topsoil. At such times the limited Mg resources of the topsoil cease to be available and the layers immediately below cannot furnish sufficient of this nutrient to meet the demands of the young trees. This phenomenon is probably aggravated by interaction between K and Mg as a result of the disproportionately large amounts of exchangeable K in layers II, III and IV. The ratios of exchangeable K to Mg in the six layers, based on milliequivalents per 100g soil values, are as follows:

I	2:1	IV	45:1
II	14:1	VI	4:1
III	14:1	VIII	0.3 : 1

When the total amounts of these two nutrients in the profile are converted to equivalent weights the overall ratio of exchangeable K to Mg is 4:1.

Assuming, in the absence of any established figure, that the removal of Mg from the forest in thinnings and logs is of the same order for radiata pine as that reported by Wright and Will (1958) for *Pinus nigra*, i.e., *ca.* 100lb/acre, then the amount of exchangeable Mg in the surface three feet of soil (approximately 77lb/acre) is barely sufficient for a single crop rotation. However, this does not take into account mineralisation of organic matter, or enrichment of the surface soil with nutrients which are obtained by tree roots from deep in the profile and are eventually returned to the soil through needlecast. The two buried, fossil topsoils, at depths of approximately six and eight feet respectively, together contain approximately 226lb/acre exchangeable Mg. The overall exchangeable magnesium content of the rooting zone may also be kept at an adequate level by the amount released by continuous weathering over the life span of a tree crop of such accessory, magnesium-rich minerals as occur in the profile. The extent to which depletion of exchangeable magnesium in layers I, VI and VIII occurred as a result of intensive cropping in the pot trial is shown in the following synopsis of plant and soil analysis:

Table 7. Exchangeable Mg contents of layers I, VI and VIII before and after intensive cropping with radiata pine seedlings, shown in conjunction with

(a) the net weight of Mg extracted by seedlings from each layer,
(b) the final crop foliar concentration of Mg, and
(c) any occurrence of visual Mg deficiency symptoms in the final crops; nutrient supplements were applied as indicated in column 4.

Layer	Soil exchangeable Mg content mg% Prior to cropping	Soil exchangeable Mg content mg% After cropping	Crop fertiliser treatment	Net uptake per 4 crops g	Final foliar concn %	Visual Mg deficiency symptoms in final crop
I	4.6	1.0	Control	.15	.11	None
		0.5	+ N, P, K	.23	.03	Marked
VI	2.4	0.3	+ N, P	.14	.02	Marked
VIII	6.7	1.4	+ N, P	.15	.05	None

Calcium

As with magnesium the resources of exchangeable calcium are mainly concentrated in the humified layers I, VI and VIII; the ash layers which lack organic matter contain substantially less.

The pot study gave no indication of any actual or incipient deficiency of this nutrient after intensive cropping. The actual content of exchangeable calcium in individual layers before and after intensive cropping were:

Table 8. Exchangeable Ca contents of layers I, II, III, IV, VI, and VIII before and after intensive cropping with radiata pine seedlings; the nutrient supplements applied to the various layers are shown in the last column.

Layer	Soil exchangeable calcium mg Ca per 100 g soil Prior to cropping	 After cropping	Fertiliser treatment
I	24	15	Control
		13	+ N, P, K
II	7	6	+ N, P, Mg
III	5	*	
IV	9	4	+ N, P, Mg
VI	24	13	+ N, P
VIII	55	24	+ N, P

* Not determined.

Supplies of this nutrient are unlikely to become limiting to productivity or thriftiness of stands in the foreseeable future.

CONCLUSIONS

The layers of bedded rhyolitic ash which make up the tree rooting zone in central Kaingaroa Forest differ markedly in their individual resources of macronutrients.

The topsoil (layer I) provides the only substantial source of readily available N, P and Mg in the upper five feet of the profile. The other three layers in this part of the profile which are almost entirely mineral, contain a large proportion of the exchangeable K content of the rooting zone, some calcium, but little else of immediate nutrient value. The humified layers ('fossil' topsoils) which lie buried to depths of approximately five and seven feet contain useful quantities of exchangeable Ca and Mg. Whereas juvenile trees have to draw heavily upon the topsoil for some years to satisfy their magnesium requirements, the deeper roots of mature trees may exploit these lower layers. If this is so, gradual replenishment of the topsoil Mg at the expense of these deeper layers would result from a higher Mg content in the needle fall after the closed canopy stage has been reached. It has yet to be established whether or not mature trees are able, over periods of several decades, to utilise any part of the substantial amounts of organic P present in the buried former surface soils. It is, however, rather doubtful since neither mycorrhizal development nor mineralisation occur to any appreciable extent below two to three feet from the soil surface.

Examination of the six main ash layers by soil chemical analysis and by an intensive cropping procedure provides independently derived estimates of nutrient supplies in this pumice soil, which agree closely.

The comparative fertility or infertility of the six layers is greatly influenced by their individual contents of organic matter and by the nature of the clay fraction. The topsoil and the two buried 'fossil' topsoil layers are humified and contrast markedly in nutrient status with the intervening three layers which are almost devoid of organic matter. Layer IV differs from the other layers in that it is composed almost entirely of lapilli. The humified layers have the highest cation exchange capacities, account for the greater part of the exchangeable Ca and Mg within the rooting zone and contain substantial amounts of organic P; the mineral layers contain the bulk of exchangeable K, but only very small amounts of exchangeable Ca and Mg.

The nature of the parent material, results of field tests and the soil properties strongly suggest that the dominant clay form throughout the rooting zone is allophane. It is recognised that this clay has properties which are capable of greatly influencing the availability of nutrients. In particular, allophane associates with the humus of surface soils, protecting it against mineralisation; it also 'fixes' both inorganic and organic phosphates.

Both soil analyses and pot trial evaluation indicate that in extensive regions of the forest having a soil profile comparable with that of the area examined, the requirements of K and Ca for healthy crops can be amply met for several rotations of exotic pines to come. The existing supplies of readily available N, P and Mg, while adequate at present, are by themselves insufficient for maintenance of the present high stand productivity and thriftiness for more than a strictly limited number of rotations, possibly two. However, the dynamic processes which occur in the soil—such as mineralisation of humus, plant-soil cycling of nutrients, N fixation and weathering—have also to be considered since they may furnish sufficient nutrients over the protracted period of a tree crop rotation to offset losses due to leaching and removal of timber. The maritime atmosphere itself can be expected to contribute further amounts, since precipitation and coastal 'aerosols' frequently contain traces of various macronutrients.

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APPENDIX

METHODS OF ANALYSIS

Total nitrogen

This was determined by the Kjeldahl semi-micro method, using Parnas Wagner apparatus as described by Metson (1956).

Phosphorus

1. Truog (readily soluble) phosphorus: extraction with ammonium bisulphate solution (.002 N H_2SO_4 buffered to pH 3 with ammonium sulphate) in a soil extractant ratio of 1 : 200 for 30 minutes on a wrist action shaker. After filtration, the phosphorus in the extract was determined by measuring the molybdophosphorus blue colour developed by the method described by Jackson (1956).
2. Citric acid soluble phosphorus: extraction with 1% citric acid using a soil : extractant ratio of 1 : 10 for 24 hours on an end-over-end shaker at 20°C. The procedure followed for both extraction and colour development was that described by Metson (1956).
3. Bray No. 2 test (Bray and Kurtz, 1945): extraction with dilute acid-fluoride. The extractant is a solution which is 0.03 N in NH_4F and 0.1 N in HCl. The soil to extractant ratio was modified to 1 : 10 and extraction was performed by shaking for one minute by hand.
4. Sodium bicarbonate extraction (Olsen *et al.*, 1954) : extraction with 0.5 M sodium bicarbonate buffered to pH 8.5. The soil to extractant ratio was 1 : 20 and extraction lasted 30 minutes on a platform shaker. P was determined in the Bray and Olsen extracts by the ascorbic acid method of Watanabe and Olsen (1965).
5. Organic phosphorus: air-dried and ignited comparable samples were extracted with N H_2SO_4 for 16 hours on an end-over-end shaker at a temperature of 20°C. The soil : extractant ratio was 1 : 200 and the samples had been previously ground to pass through a 70 mesh U.S. standard sieve. The ignition was carried out in a preheated muffle furnace at 240°C for one hour. Normal H_2SO_4 extracts all but the least readily acid soluble inorganic phosphorus. Ignition of the soil converts the organic P to the inorganic form so that the difference in the P extracted before and after ignition is taken as an estimate of the organic P content of the soil.
6. Phosphate retention: This was determined by the method described by Saunders (1964). The amount of phosphorus remaining in solution after shaking the soil sample with a buffered, standard phosphate solution for 24 hours was determined colorimetrically using molybdovanadate reagent. The percentage retention was calculated from the difference in P content of the solution before and after shaking. The ratio of soil : retention solution was 1 : 5; the retention solution was buffered at pH 4.6 and contained 1 mg/ml P.

Organic carbon

This was determined by a N.Z. Soil Bureau modification of the rapid, approximate method described by Metson, 1956. The heat generated when 15ml 4N $Na_2Cr_2O_7$ is added to a suspension of finely ground soil in 30 ml conc. H_2SO_4 facilitates oxidation of the organic matter present by chromic acid. The oxidation is partial, though quantitative, and the green colour of the trivalent chromium ion gives a direct measure of the quantity of carbon oxidised. Colour densities in this and the four phosphate determinations were measured on a 'Spekker' photoelectric absorptiometer.

Total organic matter

This was obtained by multiplying the organic carbon figure by the widely accepted conversion factor of 1.724 (Metson, 1956).

Index of K release from non-exchangeable forms

This was found by the method described by Pratt (1965) except that unground ($<$2 mm) samples were used. The samples were extracted by boiling with normal HNO_3 for 10 min. in a soil extractant ratio of 1 : 10. The soil was washed with four 15 ml portions of 0.1 N HNO_3. The potassium in the extracts was determined using a flame photometer.

Cation exchange capacity

The procedure adopted was that recommended by Metson and Blakemore (1964): a preliminary leaching with neutral N NH_4OAc to saturate the exchange sites of the soil complex with ammonium ions followed by a leaching with N NaCl to quantitatively displace the ammonium ions from the soil complex. The ammonia present in the leachate was determined by the micro-Kjeldahl method.

Exchangeable cations

These were extracted by leaching the soil samples with N NH_4OAc by the method described by Metson (1956). Strontium chloride was added to both samples and standards to give 'flame' solutions containing 1000 ppm Sr; this was to minimise the formation of refractory compounds with Al, Si and P during atomic absorption measurements (David, 1960). Calcium, magnesium and sodium were determined by atomic absorption spectrophotometry; potassium was determined by emission flame photometry.

Soil reaction

pH measurements were made using a glass electrode. The pH was measured in water at 20°C with a soil : water ratio of 1 : 2.5.