Full Length Research Paper

Changes in P nutrition and growth of radiata pine (*Pinus radiata*) seedlings on an allophanic soil under influence of P fertiliser application

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Abstract

Most of trials in New Zealand radiata pine (*P. radiata*) plantations were conducted on Podzol Soils and Mapua sandy loam soils. Few trials were conducted on Allophanic Soils in the country. A better understanding on change in P chemistry and tree growth due to the application of P fertiliser on an Allophanic Soil is important to determine appropriate management practice for the P fertiliser. A glasshouse trial was carried out to investigate changes in the soil available P, the P nutrition, growth of *P. radiata* seedlings, and to determine relationships of soil plant-available P with plant P on an Allophanic Soil, following the application of three rates of triple superphosphate (TSP) in a glasshouse. The results showed that the application of P fertilizer enhanced the P availability in the soils of radiata seedlings as measured by the Bray-2 P concentrations. The dry matter yield and the P concentrations in needles, stem, and roots of radiata pine increased also with increased rates of triple superphosphate application to a P-deficient Allophanic Soil. Furthermore, P concentration in the new shoot needles had significant logarithmic relationship with Bray-2 P concentration in the soil under the radiata seedlings. This curvilinear relationship suggests that the P concentration of new shoot needles diminishes with an increase in the plant-available P concentration (Bray-2 P) in this high-P fixing Allophanic Soil.

Keywords: Phosphorus fertilizer, *Pinus radiata*, P nutrition, growth.

INTRODUCTION

In general, exotic forests in the Southern Hemisphere countries have been established on lands having a much lower P fertility that was considered unsuitable for agricultural production than those in the Northern Hemisphere countries (Ballard, 1980). Therefore, the trees become P deficient unless P fertilisers are applied (Ballard, 1980). Currently, in many of those countries application of P fertilisers are considered an important silvi-cultural practice in maintaining and increasing forest productivity (Will, 1985). The forest plantation in New Zealand is projected to expand from 1.5 million ha in 1997 to 2.5 million ha in 2025. Under this expansion programme, it was calculated that the annual P fertiliser requirement will double the current amount required, for removing P deficiency, approximately five times the current amount required, for maintenance fertilisation,

and it will be about ten times the current amount of P required, for maximum wood production ((Payn *et al.*, 1998; Payn *et al.*, 2000). Phosphorus fertiliser application to New Zealand plantation forests was traditionally for the purpose of P deficiency correction rather than maximising wood production (Payn *et al.*, 2000).

In 1998, the entire series of trials on *P. radiata* to determine the optimum rates of P application in New Zealand were completed. Based on the results of these two trial series, up to 1 tonne of superphosphate (approximately 100 kg P ha^{-1}) was recommended for application to forest plantation. Relationships between rates of P application and foliar P concentrations were developed from the results of these trials (Payn *et al.*, 2000). However, most of those trials were conducted on Podzol Soils and Mapua sandy loam soils (Pallic Soil

formed on Moutere Gravels). Few trials were conducted on Allophanic Soils in the country.

Adams and Walker (1973) reported that there were very highly significant correlations between needle P concentration and non-occluded P, Bray-2 P and Olsen P concentrations on Mapua sandy loam soils (Pallic Soil formed on Moutere Gravels) in a 8-year-old first rotation and 10 to 14-year-old second rotation radiata pine plantations. They also reported that Bray-2 P had the highest correlation, while Olsen P had the lowest correlation with needle P concentration. Such relationships have not been reported yet for Allophanic Soils in New Zealand.

Most soils under radiata pine plantations in New Zealand are acidic and P-deficient (Ballard, 1980; Payn et al., 2000). A better understanding on change in P chemistry and tree growth due to the application of P fertiliser on an Allophanic Soil is important to determine appropriate management practice for the P fertiliser. The objectives of the present study were to investigate changes in the soil available P, the P nutrition, growth of P. radiata seedlings, and to determine relationships of soil plant-available P with plant P on an Allophanic Soil, following the application of three rates of triple superphosphate (TSP) in a glasshouse.

MATERIALS AND METHODS

Experimental design

The trial tested the effects of three rates of P fertilizer: 0, 50, and 100 mg kg^{-1} P (equivalent to 0, 50 and 100 kg ha^{-1} P, bulk density=1 g cm^{-3}, depth= 10 cm) applied as TSP (granules ground to pass through 250 μm; total P = 20.7%) to the soil. The treatments were replicated five times in a completely randomized design in a glasshouse maintained at $28^{o}C$ maximum and $13^{o}C$ minimum temperatures.

Bulk sample of soil collected from Kaweka forest, New Zealand (from a 0–10 cm depth) was used in this trial. This forest area had not received fertilizer for at least 30 years. The soil is classified as Allophanic Soil (Hewitt, 1998; Soil Survey Staff, 1999), with fine sandy loam texture, moderate medium crumb structure, non-sticky, non-plastic wet, and very friable moist, a bulk density of 0.8 mg m^{-3} and significant quantities of allophane. To remove debris, the soil was air-dried and passed through a 5 mm sieve. A subsample of soil was ground to pass through a 2 mm sieve and analysed for chemical properties (Table 1) prior to planting.

Planting and maintenance of trial

Plastic pots were used to grow the plants containing 2.5 kg of air-dried soil (Water Content = 50%, equal to 1.25

kg oven-dried mass) that mixed homogeneously with the appropriate amounts of TSP.

The seeds of radiata obtained from Forest Research Ltd., Rotorua were germinated according to the following procedure: soaked overnight in running tap water, planted in moist perlite in a box with a lid (box of 10 cm depth), and kept in a dark place at 22–24ºC. All the seeds germinated in 7 days. One week after germination, radiata seedlings were transplanted into the pots (one seedling into each pot).

A complete but –P nutrient solution (Middleton and Toxopeus, 1973) was added to all pots five months after the planting of the radiata seedlings. The nutrient solution was applied at a rate of 450 ml per pot four times during a two-week period, except the nitrogen stock solution which was applied only two times. Applications of nutrient solutions were made at 3–4 day interval. In total, each pot received 54.2 mg kg^{-1} N and 35 mg kg^{-1} K.

During growing period, the air temperature in the glasshouse was maintained at $28^{o}C$ maximum and 13ºC minimum. Soil water content was maintained at 80% field capacity by bringing the weight of pot and soil to the required weight by adding distilled water (field capacity of Kaweka forest soil was 87% gravimetric water content). The weight of soil in each pot at 80% field capacity was 2.87 kg.

Soil and plant sampling

Soil samples were collected from each treatment pot for the five replications. All soil samples were air-dried, passed through a 2 mm sieve to remove debris and stored at $4^{o}C$ for measuring soil plant-available P (Bray-2 P).

Radiata seedlings were harvested at the end of the experiment at 57 weeks (March 2, 2004) after planting these seedlings. Shoots of the seedlings were collected by cutting the plants approximately 1 cm above the soil surface. From the harvested radiata shoots, needle tips were collected by cutting the top 5 cm of the new growth in the seedlings. Stems were also retained. The stems and needles were dried in an oven at $70^{o}C$ for 48 hours and the dry weights were recorded. After removing the soils, the roots of all seedlings were washed free of soil and dried in an oven at $70^{o}C$ for 48 hours and the dry weights were recorded as well.

Chemical analysis

The soil pH was determined using a soil: water w/w ratio of 1:2.5. Soil suspensions were stirred and kept overnight at 20 ± $2^{o}C$ after which pH was determined using a pH meter equipped with a glass electrode (Blakemore et al., 1987).

The organic matter content of the soils (expressed as percentage carbon) was determined by heating the

Table 1. Selected properties of the soil (0-10 cm depth below the litter layer) at the Kaweka forest

Parameter	Value
pH (1:2.5 H_2O)	5.5
Potassium ($cmol_c$ kg^{-1})	0.28
Calcium ($cmol_c$ kg^{-1})	2.95
Magnesium ($cmol_c$ kg^{-1})	0.62
) Sodium ($cmol_c$ kg^{-1})	0.13
Carbon (%)	5.8
Nitrogen (%)	0.27
Cation exchange capacity ($cmol_c$ kg^{-1})	16
) Phosphorus retention (%)	92
Bray-2 P (mg kg^{-1})	2.8
P-total (mg kg^{-1})	262

samples in a stream of high purity oxygen in a Leco furnace to produce CO_2. The CO_2 was measured with an infrared detector (Leco Cooperation, 1996) and the quantity of that gas used to determine the total organic carbon. Cation-exchange capacity (CEC) and exchangeable cations were determined by ammonium acetate leaching at pH 7 (Blakemore et al., 1987). The concentrations of K, Ca, Mg, and Na in the leachates were determined by atomic absorption spectrometry (AAS), and the ammonium concentration was determined using an Autoanalyser (Blakemore et al., 1987).

Phosphorus retention was determined by measuring the P concentration in soil solution after 5 g soil was shaken with 25 ml solution containing 1000 µg P mL^{-1} for 16 h. In New Zealand, Bray-2 P is the common soil test used for determining P availability in radiate pine plantation soils (Hunter and Hunter, 1991; Davis, 1995; Giddens et al., 1997). Bray-2 P was determined by shaking 2.5 g of air dry soil for one minute in 25 mL of a solution containing 0.03 mol·L^{-1} NH_4F and 0.1 mol·L^{-1} HCl and measuring the P concentration in the solution by the colorimetric technique of Murphy and Riley (1962) (Blakemore et al., 1987).

The dried needles, stem, and root samples were ground using a hand-held Breve coffee grinder. The ground material was digested with a Kjeldahl digestion mixture containing 100 g of potassium sulphate and 1 g selenium powder in 1 litre of concen-trated sulphuric acid (95%–97%) (Twine and Williams, 1971). Phosphorus concentrations in the digest were measured by using a Technicon auto-analyser (Searle, 1975; Blackmore et al., 1987).

Statistical analysis

An analysis of variance (ANOVA) for a completely randomized design was performed using SAS (SAS, 2001). The least significant difference (LSD) test at $p <$

0.05, unless otherwise stated, was used to separate the means when the analysis of variance (ANOVA) results indicated that there were significant treatment effects (Steel et al., 1997). Data were square root transformed when the spread was proportional to the square root of mean and were log_e transformed when the spread was proportional to the treatment mean (Anon, 2000; Steel et al., 1997).

RESULTS AND DISCUSSION

Soil plant-available P

In New Zealand, Bray-2 P is the common soil test used for determining P availability in *P. radiata* plantation soils (Ballard, 1974; Giddens et al., 1997; Hunter and Hunter, 1991; Davis and Lang, 1991). In the present study, the soils that received no P fertiliser had very low Bray-2 P concentrations (approximately 2.8 µg P g^{-1}) (Table 2). Even after application of TSP at a rate equivalent to 100 kg P ha^{-1}, the Bray-2 P concentrations in these soils was below the critical P concentration of 12 µg P g^{-1} reported for radiata seedlings (Ballard, 1974). According to Skinner et al. (1991) in New Zealand *P. radiata* plantations, plant-available P values (Bray-2 P) in the topsoil (0-10 cm depth) vary widely, ranging from 1.0 ∝g P.g^{-1} (a Podzol Soil of Auckland) to 46.5 ∝g P.g^{-1} (a Pumice Soil of Rotorua) (Table 2).

Furthermore, the increase of the P fertiliser rate significantly ($p<0.0001$) increased Bray-2 P concentrations. The highly significant effect of the P fertiliser rate on the Bray-2 P concentrations is not surprising because the soils without P addition had a low plant-available P concentration. However, the magnitude of increase in Bray-2 P with increased P fertiliser rates (50 and 100 kg P ha^{-1} soil) is small, which was only 2-3 mg P kg^{-1}. This could be due to the high fixation of P by this Allophanic Soil. Consequently, proportionately more

Table 2. Effect of P fertiliser on Bray-2 P concentration after 57 weeks of the plant growth in soil in an Allophanic Soil in a glasshouse

P rate ($\propto$g P g^{-1} soil)	Bray-2 P concentration ($\propto$g P g^{-1} soil)
0	2.93± 0.15 c[1]
50	6.57± 0.30 b
100	9.12± 0.44 a

Note: [1]Numbers within the same column followed by the same letters are not significantly different at $p<0.05$

Table 3. Effect of TSP fertiliser rates on P concentration (%) in radiata pine seedlings after 57 weeks of plant growth in an Allophanic Soil in a glasshouse

Plant part	P rate (mg P kg^{-1} soil)		
	0	**50**	**100**
Shoot needles	0.115 ± 0.03 c[1]	0.141± 0.05 b	0.178 ± 0.03 a
Stem	0.035 ± 0.005 b	0.046± 0.005 b	0.068 ± 0.001 a
Root	0.047 ± 0.002 b	0.048± 0.003 b	0.059 ± 0.003 a

Note: [1]Numbers within the same row followed by the same letters are not significantly different at $p<0.05$

Table 4. Effect of TSP fertiliser rates on shoot, root and total dry matter yield (g pot^{-1}) of radiata pine seedlings after 57 weeks of plant growth in an Allophanic Soil in a glasshouse

Plant part	P rate (mg P kg^{-1} soil)		
	0	**50**	**100**
Shoot	12.3 ± 1.4 b	64.5 ± 2.6 a	73.4 ± 3.3 a
Root	3.2 ± 0.4 b	19.2 ± 1.5 a	21.8 ± 2.8 a
Total	15.5 ± 1.8 b	83.7 ± 4.7 a	95.2 ± 4.9 a

Note: [1]Numbers within the same row followed by the same letters are not significantly different at $p<0.05$

of the fertiliser-P applied had been converted into less available soil P fractions (Clark and McBride, 1984; Parfitt, 1989).

Plant P concentrations

The P concentration in new shoot needles for the 0 µg P g^{-1} soil treatment was lower than 0.12%, the concentration in new shoot needles commonly considered to be the deficiency threshold for 7 to 9-year old *P. radiata* trees (Mead and Gadgil, 1978; Will, 1978). Phosphorus concentrations in needles, stem and roots were significantly influenced by the rate of P fertiliser application ($p<0.0001$, $p=0.0016$, and $p=0.0038$, respectively) Table 3.

Increased P fertiliser rates significantly increased P concentration in needles, stem and roots of radiate pine. This is consistent with the effect of P rates on plant available P concentration in the soil as explained earlier. In addition, this result is also in accordance with Liu *et al*. (2004) who reported that increased P concentration in shoots of seedlings grown on soil taken from the same forest plantation with increased rates of P application.

Plant dry matter yield

The results of analysis of variance showed that the effects of P fertiliser rates was significant ($p<0.0001$) on dry matter yields of radiata shoot, root and total (shoot + root).

Shoot, root, and total radiata dry matter yield increased markedly with the additions of 50 and 100 µg P g^{-1} soil compared with the control treatment (0 µg P g^{-1} soil) (Table 4). However, there was no significant difference in shoot, root, and total dry matter yields between the application of 50 and 100 µg P g^{-1}. The
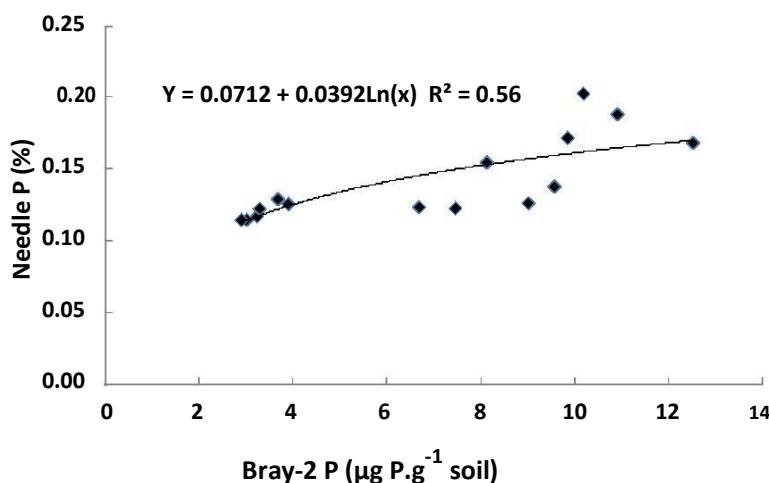
Figure 1. Relationship between new shoot needle P concentrations of radiata pine seedlings and Bray-2 P concentrations after 57 weeks of plant growth in an Allophanic Soil in a glasshouse

highly significant effects of P fertiliser rate on the dry matter yields could be due related to the native soil that had a very low plant-available P concentration (Table 1).

Relationship of Bray-2 P and plant P

The regression analysis of phosphorus concentrations in new shoot needles and Bray-2 P in the soil showed that the data fit best to logarithmic equations. Therefore, logarithmic relationship was obtained for the regression.

Phosphorus concentration in the new shoot needles had significant logarithmic relationship with Bray-2 P concentration in the soil (R^2 = 0.56, P=0.0019, Fig. 1). The curvilinear relationship of needle P concentrations with Bray-2 P concentrations suggests that the increase in new shoot needle P concentrations per unit increase in soil plant-available P concentration diminishes with increasing levels of soil plant-available P concentration Figure 1.

CONCLUSIONS

Phosphorus fertilizer application enhanced P availability in the soils of radiata seedlings as measured by the Bray-2 P concentrations. In addition, the P concentrations in needles, stem, and roots of radiata and the dry matter yield increased also with increased rates of triple superphosphate application to a P-deficient Allophanic Soil.

Furthermore, P concentration in the new shoot needles had significant logarithmic relationship with Bray-2 P concentration in the soil under the radiata seedlings.

This curvilinear relationship suggests that the P concentration of new shoot needles diminishes with an increase in the plant-available P concentration (Bray-2 P) in this high-P fixing Allophanic Soil.

REFERENCES

Adams JA, Walker TW (1973). Nutrient relationships of radiata pine in Tasman Forest, Nelson. New Zealand J. For. Sci., 5: 18-32

Anonymous (2000). Analysis of Experiments for Researchers. Course Material. Institute of Information Sciences and Technology, College of Science, Massey University, 203 pp

Ballard R (1974). Use of soil testing for predicting phosphate fertiliser requirements of radiata pine at time of planting. New Zealand J. For. Sci., 4: 27-34

Ballard R (1980). Phosphorus nutrition and fertilisation of forest trees. In: The role of Phosphorus in Agriculture. (Eds. F E Khasawneh, E C Sample and E J Kamprath) American Society of Agronomy, Wisconsin, USA. 763-804

Blakemore LC, Searle PL, Day BK (1987). Methods for chemical analysis of soils. New Zealand Soil Bureau, Scientific Report, NZ Soil Bureau, Lower Hutt, 80 pp

Clark CJ, McBride MB (1984). Cation and anion retention by natural and synthetic allophane and imogolite. Clays Min., 22: 291-299

Davis MR (1995). Influence of radiata pine seedlings on chemical properties of some New Zealand montane grassland soils. Plant Soil, 176: 255-262

Davis MR, Lang MH (1991). Increased nutrient availability in topsoils under conifers in the South Island high country. New Zealand J. For. Sci., 21: 165 – 179

Hewitt AE (1998). New Zealand soil classification. Landcare research science series No. 1. Lincoln, New Zealand: Manaaki Whenua Press, Landcare Re-search New Zealand Ltd., 133 pp

Hunter IR, Hunter JAC (1991). Apparent phosphorus uptake and change in nitrogen content of *Pinus radiata* growing on soils of different phosphorus retention, treated with superphosphate and A-grade rock phosphate. New Zealand J. For. Sci., 21: 50-61

Giddens KM, Parfitt RL, Percival HJ (1997). Comparison of some soil properties under *Pinus radiata* and improved pasture. New Zealand J. Agr. Res., 40: 409 – 416

Leco Corporation (1996). CNS-2000 Elemental Analyzer - Instruction Manual. St. Joseph (MI): LECO Corporation. 25 pp

Liu Q, Loganathan P, Hedley MJ, Skinner MF (2004). The mobilisation and fate of soil and rock phosphate in the rhizosphere of ectomycorrhizal *Pinus radiata* seedlings in an Allophanic Soil. Plant Soil, 264: 219-229

Mead DJ, Gadgil RL (1978). Fertiliser use in established radiata pine stands in New Zealand. New Zealand J. For. Sci., 8: 105-134

Middleton KR, Toxopeus MRJ (1973). Diagnosis and measurement of multiple soil deficiencies by a substractive technique. Plant Soil, 38: 219–226

Parfitt RL (1989). Phosphate reactions with natural allophane, ferrihydrite and goethite. J. Soil Sci., 40: 359-369

Payn TW, Skinner MF, Clinton PW (1998). Future nutrient requirements of New Zealand plantation forests. In: Long-term Nutrient Needs for New Zealand's Primary Industries. Occasional report No. 11. (Eds. L D Currie and P Loganathan) Fertiliser and Lime Research Centre, Massey University, New Zealand. 97-110

Payn TW, Skinner MF, Hill RB, Thorn AJ, Scott J, Downs S, Chapman H (2000) Scaling up or scaling down: the use of foliage and soil information for optimising the phosphate nutrition of radiata pine. For. Ecol. Manag., 138: 79-89

SAS (2001). SAS Institute Inc., Cary, NC, USA

Searle PL (1975). Automated colorimetric determination of ammonium ions in soil extracts with 'Technicon Autoanalyser II equipment'. New Zealand J.f Agr. Res., 18: 183–187

Skinner MF, Lowe AT, Nicholson GM, Prince J (1991). Availability of phosphorus in New Zealand forest soils. A new approach with the Bray reagent In: Soil and Plant Testing for Nutrient Deficiencies and Toxicities. Occasional report No. 5. (Eds. R E White and L D Currie) Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. 143-147

Soil Survey Staff (1999). Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys, 2nd edition. Agricultural Handbook 436, Natural Resources Conservation Service, USDA, Washington DC, USA. 869 pp

Steel RGD, Torrie JH, Dickey DA (1997). Analysis of Variance IV. Split-plot Design and Analysis. Principle and Procedures of Statistics: a Biometrical Approach. 3rd edition The McGraw-Hill Companies, Inc., New York, USA, 672 pp

Twine JR, Williams CH (1971). The determination of phosphorus in kjeldahl digests of plant materials by automatic analysis. Communication in Soil Sci. Plant Anal., 2: 485–489

Will GM (1978). Nutrient deficiencies in *Pinus radiata* in New Zealand. New Zealand J. For. Sci., 8: 4-14

Will GM (1985). Nutrient Deficiencies and Fertiliser Use in New Zealand Exotic Forests. FRI Bulletin No. 97. New Zealand Forest Service, Forest Research Institute, Rotorua, New Zealand