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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 µg P.g^{-1} (a Podzol Soil of Auckland) to 46.5 µg 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 (µg P g^{-1} soil)	Bray-2 P concentration (µg 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

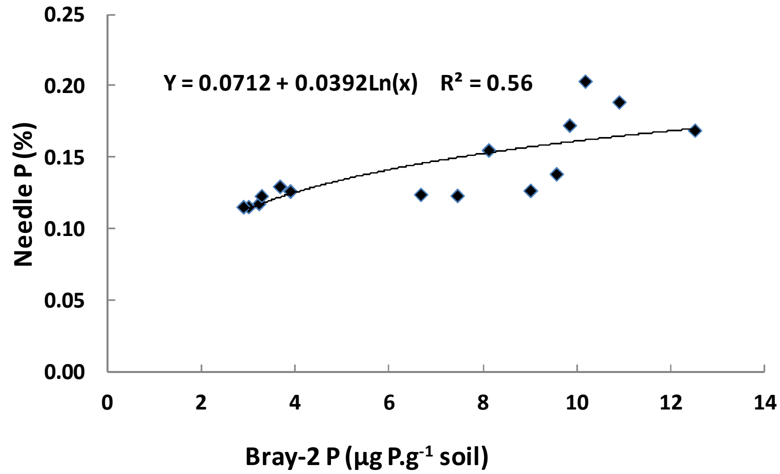

Figure 1. Relationship between new shoot needle P concentrations of radiata pine seedlings and Bray-2 P concentrations after 57 weeks of plant growth in an Allophanic Soil in a glasshouse

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.

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