Research paper

Growth Response of Second-Rotation *Pinus radiata* on an Orthic Allophanic Soil to P Fertilizer and Weed Control

Achmad Arivin Rivaie,[1,3] Russ Williams Tillman[2]

【Summary】

Information on the interactive effects of soluble and less-soluble P fertilizers and weed control on the growth and P nutrition of second-rotation radiata pine (*Pinus radiata*) trees is required to determine appropriate management practices of P fertilizer and understory vegetation in radiata pine forest plantations. A field trial was conducted to investigate the growth of second-rotation *P. radiata* and determine the relationships between needle P concentrations and soil P forms in an Orthic Allophanic soil 2 yr after application of 4 doses (0, 50, 100, and 200 kg P ha^{-1}) of P applied in 2 forms of P fertilizer (triple superphosphate (TSP) and Ben-Guerir phosphate rock (BGPR)) in combination with 2 weed control practices (weeds present and weed-free). The application of TSP and BGPR increased the tree needle P concentration although the needle P concentrations before fertilizer application were marginally higher than the critical P concentrations, despite the soils being P deficient according to traditional soil P tests (Bray and Olsen tests). The application of P fertilizers had no effect on tree growth during the 2-yr period of the trial, although it increased radiata pine needle P concentrations. However, weed removal increased the diameter at breast height (DBH) and basal area (BA). Trees in this forest site had needle P concentrations higher than the critical P concentration. This suggests that the growth increase due to weed removal treatment was probably due to an increase in the availability of soil water and nutrients other than P. The needle P concentrations of *P. radiata* can be predicted by soil tests, and Bray-2 P, Olsen P, resin-P_i, and NaOH-P_i tests. Of these soil tests, Bray-2 P seemed to be the best test for predicting soil P availability for radiata pine. P concentrations in the needles had a strong relationship with the NaOH-P_i fraction in the soil but it had only a weak relationship with the H_2SO_4-P_i fraction. These results suggest that radiata pine was probably taking up P more from the pool of P-adsorbed onto allophane and Fe+Al oxides (NaOH-P_i) than from the Ca-P pool in this high P-fixing acidic soil.

Key words: fertilizer, *Pinus radiata*, phosphorus, weed control.

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研究報告

放射松二代林於正鋁英土對磷肥與除草的生長反應

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摘　要

研究放射松(*Pinus radiata*)於可溶性與略溶性磷肥與除草的交互作用下其磷營養與生長反應，是決定放射松二代林磷肥施用與下層植被適當管理的必要措施。包括二型磷肥(重過磷酸鈣、本吉爾磷礦粉)、四級用量(0、50、100、200公斤磷/公頃)與有無除草等試驗組合，於生長於正鋁英土的放射松二代林施用二年後，進行林木生長分析以及針葉磷與土壤磷濃度的相關性分析。試驗結果顯示，二型磷肥的施用皆可增高針葉的磷濃度。依據傳統土壤磷Bray and Olsen的測定法，雖然針葉磷濃度在施肥前已略高於標準磷濃度，而土壤磷濃度卻是呈磷缺乏的狀態。二年磷肥的施用雖未影響林木生長，其針葉磷濃度仍有增加。然而，除草的確能增加胸高直徑與樹基直徑。由於該處針葉磷濃度已高於標準磷濃度，因此除草之增加林木生長，並非僅是幫助磷肥吸收，亦可能是幫助水分與其它土壤養分的吸收。由土壤Bray-2 P、Olsen P、resin-P_i及NaOH-P_i的測定結果顯示，針葉磷濃度可由土壤磷濃度預估。其中，土壤Bray-2 P的測定最能代表土壤有效磷的濃度。針葉磷濃度與土壤NaOH-P_i的測定有較高的相關性，但與H_2SO_4-P_i的測定有較低的相關性。據此結果推論，放射松利用此高固定磷酸性土壤的途徑，主要是藉由吸取附著於鋁英與鐵鋁氧化物(NaOH-P_i)上的磷，而不是鈣磷。

關鍵詞：肥料、放射松、磷、除草。

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INTRODUCTION

Silviculture practices in current second-rotation *Pinus radiata* plantations, especially in New Zealand, are trending towards wider tree spacing and lower initial stocking of *P. radiata* trees, and also increased rates of phosphorus (P) fertilizer application (Payn et al. 2000). Wider tree spacing creates the potential for increased weed growth in forest stands due to increased light and greater nutrient resources (Gadgil et al. 1988, Payn et al. 1998). Therefore, the P response of radiata pine trees following P fertilizer application under a wider tree spacing condition is expected to be more influenced by interactions among the applied P fertilizer, the tree, and understory vegetation than was the case in the past. Phosphorus fertilizer has been routinely applied to New Zealand *P. radiata* plantations, where necessary, since the 1960s (Ballard and Will 1978, Payn et al. 2000). The appropriate rates of P fertilizers for first-rotation *P. radiata* are well established (Hunter and Graham 1982, 1983, Hunter and Hunter 1991). However, very little information is available on the appropriate rates of P for second-rotation *P. radiata* under current silvicultural regimes.

Studies have shown that reactive phosphate rocks (RPRs) are suitable for permanent pastures and crops which have a long growing season and do not have short-term requirements for high levels of P, on soils with pH < 6 (in water), and in areas with a mean annual rainfall of > 800 mm that is well distributed throughout the year (Chien et al. 1987, Harrison and Hedley 1987, White et al. 1989, Bolan and Hedley 1990, Rajan et al. 1994, Indiati et al. 2002, Szilas et al. 2007). However, only a few studies have been conducted on the direct application of phosphate rocks to radiata pine plantations, especially on allophanic soils (Hunter and Graham 1983, Hunter and Hunter 1991).

Relationships of needle P concentration of first-rotation *P. radiata* with soil P concentration were determined in some studies. Ballard (1970) reported highly significant relationships between the needle P concentration of 40-yr-old radiata pines and plant-available soil P extracted by Bray-2 and Olsen extractants on Waikare clay and Mata clay hill soils (secondary podzolic soils in a semimature to submature stage of development). Meanwhile, Adams and Walker (1973) reported that there were very highly significant correlations between needle P concentrations and non-occluded P, Bray-2 P, and Olsen P concentrations on Mapua sandy loam soils (Pallic soil formed on Moutere gravels) in an 8-yr-old first rotation and 10~14-yr-old second-rotation radiata pine plantations. Such relationships have not been reported yet for allophanic soils.

Weed control operations using herbicides are now common when establishing *P. radiata* plantations in the country (Richardson et al. 1993, 1996). These practices are recommended because many studies have shown that the growth and survival of *P. radiata* trees significantly increased when competitive weed species were removed in a wide range of soil types in New Zealand (Richardson et al. 1993, 1996, Mason and Milne 1999, Watt et al. 2003a, b). Although understory vegetation frequently causes harmful effects due to competition, interactions between some understory species and *P. radiata* have been shown to provide beneficial effects to the tree. For example, Richardson et al. (1996) reported that some species of grass, herbaceous broadleaves, and buddleia significantly increased P concentrations in needles of 3-yr-old radiata pine trees, whereas broom, gorse, lotus, and pampas had no effect on needle P concentrations.

Changes in current silvicultural regimes of radiata pine plantations have created a need for more information on the interactive effects of soluble and less-soluble P fertilizers and weed control on the growth and P nutrition of the trees. This information is required to determine appropriate management practices for P fertilizer and understory vegetation in radiata pine forest plantations. The objectives of the present study were to investigate the growth of second-rotation *P. radiata* and determine relationships between needle P concentrations and soil P forms in an Orthic Allophanic soil 2 yr after application of different rates of 2 P fertilizers (triple superphosphate (TSP) and Ben-Guerir phosphate rock (BGPR)) with 2 weed control practices.

MATERIALS AND METHODS

Site description

The study area was conducted at the Kaweka forest, 70 km northwest of Hastings, New Zealand located at 450~600 m in elevation. The experiment was begun in September 2000 (through the Sustainable Management of Forest Ecosystems (SMFE) Programme) by New Zealand Forest Research, Ltd. The soil is classified as an Orthic Allophanic soil (Hewitt 1998) (Hapludands, Soil Survey Staff 1999), and has a fine sandy loam texture, moderate to medium crumb structure, a bulk density of 0.70 g cm^{-3}. Selected chemical properties of the soil are presented in Table 1.

The climate of the Kaweka forest is cool and humid (with a mean annual relative humidity of 70%), the mean annual rainfall is approximately 1412 mm, and the area has no pronounced dry period. The mean annual temperature is 12.6℃, with a February maximum monthly mean of 16.3℃ and a July minimum of 5.5℃. During the experimental period (2001 and 2002), the rainfall totals for 2001 and 2002 were 1285 and 1280 mm, respectively (National Institute of Water and Atmospheric Research, personal communication, 2004).

Table 1. Selected properties of the soil (0~10 cm in depth below the litter layer) at a forest site

Parameter	Value
pH (1: 2.5 H_2O)	5.70
K (cmol$_c$ kg^{-1})	0.29
Ca (cmol$_c$ kg^{-1})	2.90
Mg (cmol$_c$ kg^{-1})	0.58
Na (cmol$_c$ kg^{-1})	0.12
SO_4 (μg S g^{-1})	29.30
C (%)	5.60
N (%)	0.27
CEC (cmol$_c$ kg^{-1})	14.00
P retention (%)	92.00
Bray-2 P (μg g^{-1})	4.00
Olsen P (μg g^{-1})	3.00
Resin-P_i (μg g^{-1})	1.00
NaOH-P_i (μg g^{-1})	39.00
NaOH-P_o (μg g^{-1})	130.00
H_2SO_4-P_i (μg g^{-1})	17.00
Residual-P (μg g^{-1})	61.00
Total P* (μg g^{-1})	248.00

*Sum of resin-P_i, NaOH-P_i, NaOH-P_o, H_2SO_4-P_i, and residual-P.

The trees were 4~5 yr-old second-rotation radiata pines. They were planted in 1995~1996 (at a stocking rate of 1000 stems ha^{-1}). Fertilizer had not been applied to either the first-rotation or to the second-rotation trees at any time. The predominant understory species at this forest site were bracken fern (*Pteridium esculentum*), some manuka (*Leptospermum scoparium*) and brown top (*Agrostis capillaries*).

Experimental design

The experiment tested the effects of 4 doses (0, 50, 100, and 200 kg P ha^{-1}) of P applied in 2 forms of P fertilizer, a soluble form TSP and a less-soluble form ("as received" BGPR, mined in Morocco), in combination with weed control (weeds present and weed-free). The water and 2% citric acid soluble P concentrations of the fertilizers are presented in Table 2. The 2% citric acid solubility of the BGPR in the as-received state was 28% of the total P content. This value is close to the 30% value above which PRs are commonly classified as reactive PRs (White et al. 1989). The treatments were replicated 4 times in a split-plot design.

Each P rate constituted the main plots. Plot sizes were 15×15 m plus a treated buffer 5 m wide. Each main plot was divided into 2 split-plots constituting the 2 weed control treatments. Each weed split-plot consisted of 30 trees of which 20 trees were used for

Table 2. Chemical characteristics of the P fertilizers used for the trial

Fertilizer	Total P (%)	2% Citric acid-soluble P (%)	Water-soluble P (%)
TSP	20.5	100	93
BGPR*	13.2	28	< 1

*Particle size distribution: 75% < 0.25 mm, 85% < 0.50 mm, 90% < 1.00 mm.

measurement, while the weed-free split-plot consisted of 15 trees with 5 trees measured. Soil samples were taken from the 15×15-m internal plots. Weeds in the weed-free subplots were cut with a scrub-bar and placed on the soil surface at the start of the trial (12 September 2000). During the trial period, the weeds were controlled by spraying with Roundup (Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, Missouri, USA) in December 2000, and May and October 2001, and with a terbuthylazine/hexazinone mix in February 2002. Soil samples were taken from the 15×15-m internal plots. The P fertilizers were applied by hand to the entire surface of the experimental plots in October 2000.

Soil sampling and chemical analysis

In December 2002, soil samples were collected using a 2-cm-diameter soil corer. Twenty soil cores per plot were taken (spaced uniformly throughout the plot with each one 1.5 m from the stem of a tree measured) at soil depths of 0~10 cm, and the cores for each treatment were combined. All soil samples were air-dried and passed through a 2-mm sieve to remove debris (obvious roots and foliage), and the sieved samples were stored for chemical analyses. Samples of soils were also collected from the 4 blocks before the experiment began and were analyzed to determine the soil P status and soil properties before starting the trials.

The soil pH was measured in a water suspension (using a soil: solution weight ratio of 1: 2.5) after the suspensions were shaken for 24 h on a reciprocal shaker.

The organic matter content of the soils (expressed as the percentage carbon) was determined by heating the 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 Corporation 1996) and the quantity of that gas was used to determine the total organic carbon (TOC).

The cation-exchange capacity (CEC) and exchangeable cations were determined by ammonium acetate leaching at pH 7. 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 (an index of P fixation) was determined by measuring the P concentration in the soil solution after 5 g of soil was shaken with 25 ml of a solution containing 1000 μg P ml^{-1} for 16 h. Bray-2 P was determined by shaking 2.5 g of air-dried soil for 1min in 25 ml of a solution containing 0.3 M NH_4F and 0.1 M HCl and measuring the P concentration in a solution by the colorimetric technique of Murphy and Riley (1962) (Blakemore et al. 1987). Olsen P was determined by shaking 1 g of air-dried soil in 20 ml of 0.5 M $NaHCO_3$ (pH 8.5) for 30 min in an end-over-end shaker (Blackmore et al. 1987) followed by measuring the P concentration in the solution by the colorimetric technique of Murphy and Riley (1962).

The concentrations of resin-P_i, NaOH-P_i, and H_2SO_4-P_i were measured using the sequential P-extraction procedure based on the method of Hedley et al. (1994) by first extracting 0.5 g of air-dried soil with a cation (Na^+-form) and anion (HCO_3^--form) exchange resin membrane to determine resin-P_i, followed by 0.1 M NaOH extraction and determining the inorganic P (NaOH-P_i) and labile organic P (NaOH-P_o) in the extract. The soil residue was further extracted with 0.5 M H_2SO_4 (H_2SO_4-P_i). The P concentrations in the above extracts were measured by the colorimetric technique of Murphy and Riley (1962). The above P fractions delineated by this method approximately corresponded to the following soil P pools (Table 3).

The P_i uptake by the plant from the soil was reported to mainly be from the resin-P_i fraction, but the 0.1 M NaOH-P_i fraction can also supply P to plants in the long term. These 2 fractions can be grouped together and are called labile-P_i (Hedley et al. 1982, Trolove et al. 2003).

Foliage sampling and chemical analysis

In March 2003 (29 mo after fertilizer treatments), foliage samples were collected. The needles from secondary branches in the upper 1/3 of the crown were randomly sampled from 10 trees per plot. Samples were oven-dried at 70℃ to a constant weight and then ground to < 1 mm before chemical analysis. Five millilitres of concentrated HNO_3 (99%) was added to 0.25 g of dried and ground foliage in a Pyrex tube and digested at 150℃ for about 20 min (until the digest was clear). After cooling, 1.5 ml of 30% H_2O_2 was added, and the digestion continued for 1 h. After further cooling, the sample was diluted with 25 ml of deionized water, and the P concentration was determined using inductively coupled plasma (ICP) spectrometry. All results were corrected to oven-dry weights at 100℃ (Leco Corporation 1996).

Tree growth measurement

In September 2002 (24 mo after fertilizer and weed treatments), the tree height, diameter at breast height (DBH), and basal area (BA) were measured on 20 trees in the weed-containing sub-plot treatment, while in the weed-free sub-plot, measurements were taken from 5 trees. DBH was measured at 1.4 m above ground. BA was calculated as the sum of the sectional areas of all stems (1000 stems ha^{-1}) at breast height, expressed in square meters (MacLaren 1993).

Statistical analysis

Analysis of variance (ANOVA) for a split-plot 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 there were significant treatment effects (Steel et al. 1997).

RESULTS AND DISCUSSION

Needle P concentration

The application of P fertilizers significantly ($p < 0.0001$) increased needle P concentrations. Neither weed control nor interactions between P fertilizer doses and weed control had significant effects on needle P concentrations.

The needle P concentrations in the control treatment (no P fertilizer added) soil were approximately at the level considered satisfactory for the growth of radiata pine (0.13% foliar P, Mead and Gadgil 1978, Will 1978) (Table 4). The application of BGPR beyond

Table 3. P fractions measured in the sequential P-extraction procedure based on Hedley et al. (1994) and Short et al. (2007)

P fraction	Chemical nature of soil P
Resin-P_i	Inorganic P that is freely available to the plant
0.1 M NaOH-P_i	Inorganic P absorbed onto Fe and Al hydrous oxides and allophane
0.1 M NaOH-P_o	Organic P absorbed onto Fe and Al hydrous oxides and allophane
0.5 M H_2SO_4-P_i	Predominately calcium phosphates or apatite-type P minerals, some P occluded in Fe minerals
Residual-P	Recalcitrant inorganic P or structural and stable organic P in organo-mineral complexes

Table 4. Needle P concentrations (%) 29 mo after P fertilizer application

P dose (kg P ha^{-1})	Needle P (%)
0	0.137 d*
50 TSP	0.159 c
100 TSP	0.175 ab
200 TSP	0.188 a
50 BGPR	0.160 c
100 BGPR	0.165 bc
200 BGPR	0.163 bc

*Numbers within the same column followed by the same letter do not significantly differ at $p < 0.05$. TSP, triple superphosphate; BGPR, Ben-Guerir phosphate rock.

a 50 kg P ha^{-1} dose had no significant effect on needle P concentrations (Table 4). But the application of TSP at 200 kg P ha^{-1} produced higher needle P concentrations than the application of TSP at 50 kg P ha^{-1}.

There was no needle P concentration response to the application of BGPR beyond 50 kg P ha^{-1} (Table 4). But the application of TSP at 200 kg P ha^{-1} produced higher needle P concentrations than the application of TSP at 50 kg P ha^{-1}. The needle P concentration obtained from the application of BGPR at a dose of 50 kg P ha^{-1} was equal to that from the application of TSP at the same dose, and it was higher than the critical P concentration of 0.13% considered necessary to produce maximum tree growth (Mead and Gadgil 1978, Will 1978). These results suggest that the low-cost BGPR can be used to maintain satisfactory needle P concentrations, instead of the more-expensive manufactured P fertilizer, TSP, in this P-deficient acidic soil for at least 2 yr after fertilizer application (the duration of the trial).

With the application of BGPR at doses beyond 50 kg P ha^{-1}, the needle P concentrations were slightly lower than those with the application of TSP, suggesting that BGPR was slightly less effective than TSP in increasing needle P concentrations at high P rates. But such high rates are not needed to maintain satisfactory needle P concentrations for the first 2 yr after fertilizer application, because the needle P concentrations at these P doses were higher than the critical P concentrations considered necessary to produce maximum tree growth.

Other studies also showed that the more-soluble superphosphate fertilizer was more effective than phosphate rock fertilizer in increasing needle P concentrations. Hunter and Graham (1983) studied the response of radiata pine (4- to 7-yr-old stands) to the application of a single superphosphate and 3 phosphate rocks (A grade rock, C grade rock, and “citraphos” from Christmas Island) at rates of 0, 75, and 150 kg P ha^{-1} to 3 P-deficient soils (Bray P 1~2 μg P g^{-1} soil) of contrasting P retention capacities (P retentions of 93, 48, and 0%; soil pH values of 5.4, 4.9, and 4.5, respectively) in the North Island of New Zealand. They reported that 3 yr after P application, the effectiveness of the fertilizers in increasing needle P concentration in all 3 soils had decreased in the order of superphosphate ≥ A grade rock ≥ citraphos > C grade rock. This order of decreasing effectiveness of the fertilizers followed the same order as the solubilities of these fertilizers in 2% citric acid.

Furthermore, Mead (1974) studied the response of radiata pine (a 7-yr-old stand) to a single superphosphate and Christmas Island ‘C’ phosphate fertilizers on another P-deficient soil (P retention 40%, pH 4.7) in the Maramarua forest in the North Island of New Zealand. No soil P test value for this site was reported. The trial had 4 treatments: (a) control (no P added), (b) 52 kg P ha^{-1} as superphosphate, (c) 52 kg P ha^{-1} as Christmas Island ‘C’ phosphate rock, and (d) 104 kg P ha^{-1} as Christmas Island ‘C’ phosphate rock. The trees were extremely P deficient as reflected in the extremely low needle P concentrations (0.081~0.086% P) before applying the fertilizers. The P fertilizer treatments had no significant effect on the needle P concentrations after 2, 4, and 6 yr. However, the P fertilizer treatments showed a significant effect on needle P concentrations after 8 yr. The mean needle P concentrations for treatments a, b, c, and d after 8 years were 0.070, 0.100, 0.082, and 0.090% P, respectively. Though Mead (1974) reported tree yield responses to P fertilizer application from the 2nd year after P application, the response curve was either linear or had a significant positive quadratic component indicating that even the highest rate of P application was insufficient to produce the highest potential tree growth.

Tree height

At this forest site, there was no tree height responses to the P fertiliser (Table 5), weed control (Table 6) or their interaction treatments 24 mo after application of P fertilizers.

In the control treatment (no P fertilizer added) at the study site, the radiata pine needle P concentrations were approximately at the level considered satisfactory for the growth of radiata pine (0.13% foliar P, Mead and Gadgil 1978, Will 1978). This likely explains why there was no growth response to P fertilizer application in this forest. Hunter and Graham (1983) studied the growth response of 4-yr-old radiata pine (with a foliage P concentration of 0.010%) to the application of P fertilizers (superphosphate, Christmas Island ‘A’, Christmas Island ‘C’, and citraphos from Christmas Island at rates of 75 and 150 kg P ha^{-1}) on a slightly P-deficient soil (an old deeply weathered ash soil, with Bray-1 P of 2 μg P g^{-1} soil and P retention of 93%). They found that there was no significant growth response to treatments up to 3 yr after P fertilizer application. It is likely that a rapid response (in less than 2 yr after P fertilizer application) to P fertilizer is possible only in soils which are severely P-deficient and have low to medium P-retention capacities. For example, Mead (1974) observed that 2 yr after P fertiliser application (superphosphate at 52 kg P ha^{-1} and Christmas Island ‘C’ at 52 and 104 kg P ha^{-1}), the height of 7-yr-old *P. radiata* stands had significantly increased on a P-deficient clay soil (with a medium P retention of 40% and a foliage P concentration of 0.065%) at the Maramua forest.

Table 5. Tree height, diameter at breast height (DBH), and basal area (BA) after 24 mo of P fertilizer application

P dose (kg P ha^{-1})	Height (m)	DBH (cm)	BA (m^2 ha^{-1})
0	7.31	15.09	17.51
50 TSP	7.36	15.99	19.42
100 TSP	7.65	14.76	16.71
200 TSP	7.36	15.42	17.55
50 BGPR	7.38	15.19	17.77
100 BGPR	7.71	15.61	17.94
200 BGPR	7.64	14.92	16.66

TSP, triple superphosphate; BGPR, Ben-Guerir phosphate rock.

Table 6. Tree height, diameter at breast height (DBH), and basal area (BA) after 24 mo of weed control application

Weed control	Height (m)	DBH (cm)	BA (m^2 ha^{-1})
Weed-containing	7.46	15.04 b*	15.78 b
Weed-free	7.52	15.53 a	19.53 a

*Numbers within the same column followed by the same letter do not significantly differ at $p < 0.05$.

DBH

As observed for tree height, there was no DBH response to the P fertilizer (Table 5).

However, the effect of weed control on DBH was significant ($p < 0.0458$) (Table 6**)**. There was no interaction between P fertilizer rates and weed control on DBH as reported for tree height.

Radiata pine growth in this forest was not likely to have been restricted by the lack of P as the needle P concentrations were higher than the concentrations of this element required for maximum growth (Table 4). Therefore, the increase in DBH at the forest site was probably due to weed removal treatment increasing the availability of soil water and/or nutrients other than P. Nambiar and Zed (1980) reported that water stress in *P. radiata* caused by the presence of weeds, such as Yorkshire fog grass, sorrel, flat weed, bracken, subterranean clover, and ryegrass, dramatically reduced the stem diameter of trees even though a complete fertilizer was applied. They reported that the stem diameters in weed-free plots were 5.8-times higher than those in weed-containing plots. Richardson et al. (2002) reported that the diameters of radiata pines increased with the removal of broom, and this was due to the increased soil water content in the root zone. Meanwhile, Watt et al. (2003b) reported that in the 2nd year after planting of radiata pine seedlings in a dryland site at Canterbury, the competition for water between radiata pines and broom significantly reduced the root collar diameter growth of the pines. The predawn water potential in the needles of radiata pines in the absence of broom never fell below -1 MPa compared to -4 MPa in radiata pines in the presence of broom during the very dry autumn period.

Furthermore, in the present study, the effect of the weed control treatment on needle N concentrations was significant ($p < 0.0058$). There was no interaction between P fertilizers and weed control on needle N concentrations. Weed removal significantly increased needle N concentrations (Table 7). This is consistent with findings of many others. Nambiar and Zed (1980) who studied the effect of weed control on the growth of young radiata pines on a fertile sandy soil in a dry environment, at Mount Gambier, South Australia, reported that 1 yr after transplanting pine seedlings, the removal of weeds significantly increased needle N, P, and K concentrations. Clinton et al. (1994) who studied the effects of pasture on the nutrient uptake by 4-yr-old radiata pines on a Templeton silt loam, Rangiora, New Zealand, also reported that removal of pasture vegetation herbs (perennial ryegrass, white clover, and cocksfoot) significantly increased radiata pine needle N, P, and Mg concentrations (by 65, 74, and 76%, respectively).

BA

As with the DBH, BA was significantly ($p < 0.0014$) influenced by weed control (Table 6). As with tree height and DBH, the P fertilizer doses had no effect on BA (Table 5). There was also no interaction between P fertilizer doses and weed control on BA.

As in the case of DBH, the increase in BA was probably due to weed removal increasing the soil water availability during the dry season. Watt et al. (2003b) in their study found that 3 yr after removal of broom, BA had significantly increased compared to that in the presence of broom. The predawn water potential in the needles of radiata pine in the

Table 7. Needle N concentration (%) after 29 mo of weed control application

Weed control	Needle N (%)
Weed-containing	1.52 b*
Weed-free	1.60 a

*Numbers within the same column followed by the same letter do not significantly differ at $p < 0.05$.

presence of broom was lower than that in radiata pine in the absence of broom. They also found that the BA was a more-sensitive indicator of competition between radiata pine and broom compared to the ground line diameter, height, and crown diameter. In their study, the BA of trees in broom-free plots increased 12-fold over the course of 3 yr, while, the BA in plots with broom increased only 2-fold. Similarly, Richardson et al. (2002) reported that weed removal significantly increased the BA of *P. radiata* and explained that this was due to an increase in root-zone water content in plots without weeds compared to that in plots with weeds as reported in the previous section.

Relationship of needle P and soil P forms

Needle P concentrations were regressed against different soil P tests (Bray-2 P, Olsen P, resin-P_i, NaOH-P_i, and H_2SO_4-P_i). Needle P concentrations had significant logarithmic relationships with the 5 soil P test values ($r^2 = 0.74$, $p < 0.0001$; $r^2 = 0.66$, $p < 0.0001$; $r^2 = 0.69$, $p < 0.0001$; $r^2 = 0.52$, $p < 0.0001$; and $r^2 = 0.14$, $p = 0.0344$, respectively) (Fig. 1a~e).

The r^2 value for the Bray-2 P test was the highest ($r^2 = 0.74$, $p < 0.0001$), suggesting that the Bray-2 P soil test was the best for predicting soil P availability for radiata pine. The curvilinearity of the relationships indicates that the increase in needle P concentrations per unit increase of plant-available soil P diminished with an increase in the plant-available soil P concentration.

The Bray-2 P extractant, 0.03 M NH_4F + 0.1 M HCl, is known to dissolve P associated with Ca, Fe, and Al (Mehlich 1978). The fact that the Bray-2 P soil test had the highest correlation with needle P concentrations suggests that radiata pine trees are taking up P from 1 or more of the P pools of Ca-P, Fe-P and Al-P. The NaOH-P_i concentration, a measure of P adsorbed onto allophane and Fe and Al oxides, also had a strong relationship ($r^2 = 0.52$, $p < 0.0001$) with the needle P concentration (Fig. 1d). But the H_2SO_4-P_i concentration, a measure of P associated with Ca, had only a weak relationship ($r^2 = 0.14$, $p = 0.0344$) with the needle P concentration (Fig. 1e). These relationships suggest that radiata pine trees were taking up more P from the pool of P-adsorbed onto allophane and Fe + Al oxides (NaOH-P_i) than from the Ca-P pool in this soil.

CONCLUSIONS

The application of the P fertilizers (TSP and BGPR) can increase tree needle concentrations within 2 yr after application although when the needle P concentrations before fertilizer application were marginally higher than the critical P concentration, despite the soils being P-deficient according to traditional soil P tests (Bray and Olsen tests).

However, the application of P fertilizers had no effect on tree growth during the 2-yr period of the trial, although it increased radiata pine needle P concentrations. The reason for the absence of a growth response to the application of P fertilizer is that the trees were not severely P-deficient as indicated by the needle P concentrations of unfertilized trees, which were higher than the critical P concentration considered to produce maximum radiata pine yield. Another reason could be the short-term duration of the study. The tree growth response to P fertilizer application may be a slow process, and therefore, the trees showed no growth response within 2 yr after fertilizer application. However, weed removal increased tree height, diameter at breast height (DBH), and basal area (BA). As the trees in this forest had needle P concentrations higher than the critical P concentration, hence, the growth increase due to weed removal treatment was probably due to increases in the availability of soil water and nutrients other than P.

The needle P concentrations of *P. radiata* can be predicted by soil tests, and Bray-2 P, Olsen P, resin-P_i, and NaOH-P_i tests. The Bray-2 P soil test was the best for predicting soil P availability to radiata pine. The NaOH-P_i concentration also had a strong relationship with the needle P concentration, whereas the H_2SO_4-P_i concentration had only a weak

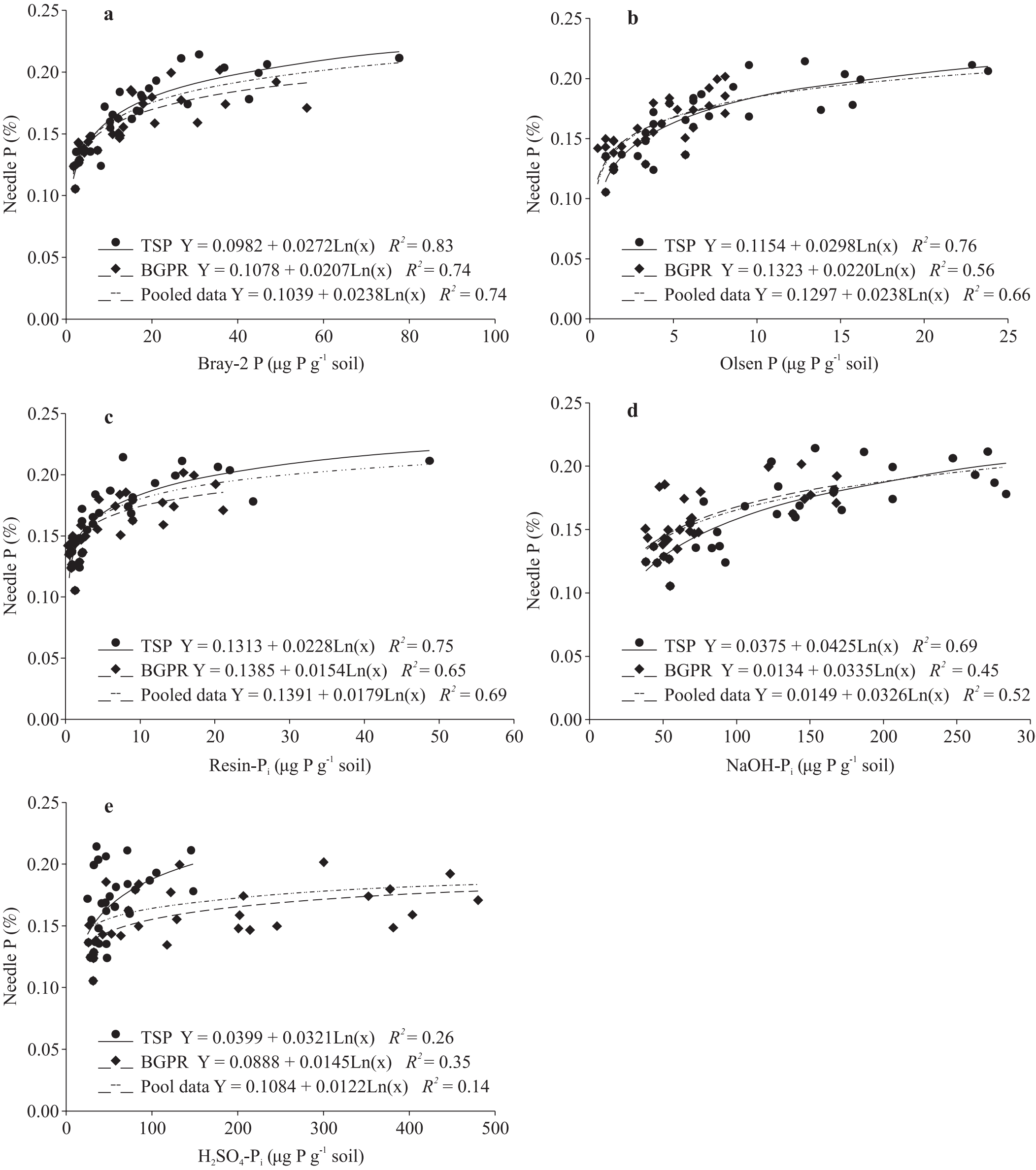

Fig. 1. Relationships between needle P concentrations and P extracted by different soil P tests (Bray-2 P (a), Olsen P (b), resin-P_i (c), NaOH-P_i (d), and H_2SO_4-P_i (e) concentrations) after 29 mo of treatment application in an Orthic Allophanic soil.

relationship with needle P concentrations. These relationships suggest that radiata pine was probably taking up more P from the pool of P-adsorbed onto allophane and Fe + Al oxides (NaOH-P_i) than from the Ca-P pool in this high P-fixing acidic soil.

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