UNDERSTOREY EFFECTS ON PHOSPHORUS FERTILISER RESPONSE OF SECOND-ROTATION *Pinus radiata*

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Soil Science at Massey University, Palmerston North, New Zealand.

Massey University

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To the Memory of

My Late Parents (Pak dan Ibu)

For their enormous love, care and guidance

Abstract

The current silvicultural regimes of *Pinus radiata* plantations in New Zealand with wider initial tree spacings have created the potential for increased growth of understorey vegetation. A consequence of this is that the response of *P. radiata* to P fertiliser is expected to be more influenced by the interaction between the P fertiliser, the tree and the understorey vegetation than was the case in the past.

The objectives of this study were to investigate the influence of different rates of a soluble and a sparingly-soluble P fertiliser (Triple superphosphate and Ben-Geurier phosphate rock) and weed control, and their interactions, on soil P chemistry and the growth and P uptake of 4-5-year-old second-rotation *P. radiata* on an Allophanic Soil (Kaweka forest) and a Pumice Soil (Kinleith forest).

The results showed that the application of P fertilisers had no effect on *P. radiata* growth at both field trial sites two years after this treatment, although it increased radiata needle P concentration. However, at both sites, the understorey vegetation removal treatment increased tree diameter at breast height and basal area. At the highly P-deficient (Bray-2 P 4 $\mu g\ g^{-1}$) Kaweka forest, the presence of understorey (bracken fern and some manuka) reduced resin-P_i and Olsen P concentrations, but at the moderate P fertility (Bray-2 P 13 $\mu g\ g^{-1}$) Kinleith forest, the understorey (Himalayan honeysuckle, buddleia and some toetoe) increased Bray-2 P, resin-P_i, and Olsen P concentrations.

A glasshouse study on *P. radiata* seedlings was conducted to test the hypothesis that when ryegrass (*Lolium multiflorum*) is grown with *P. radiata*, it increases radiata needle P concentration, while when broom (*Cytisus scoparius* L.) is grown with *P. radiata*, it has no effect. The acid phosphatase activity in the rhizosphere of *P. radiata* was higher when radiata was grown with broom than that when it was grown with ryegrass. This is consistent with the higher P concentration in needles of radiata grown with broom than that of radiata grown with ryegrass, in the absence of P fertiliser addition. However, when P fertiliser was added (50 and 100 μg P g^{-1} soil) the needle P concentration of radiata grown with broom was lower than that when radiata was grown with ryegrass.

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A. Arivin Rivaie Palmerston North, December 2004

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Chapter 1

Introduction

1.1 Background

Pinus radiata in New Zealand is planted across a range of climatic and soil conditions on approximately 1.5 million hectares of land, and constitutes 95% of the planted forest in 1997. This area is projected to expand to 2.5 million hectares by 2025. As an export earner, the forest industry in 1997 occupied third place behind the dairy industry and tourism (Payn *et al.*, 1998).

Recently, radiata pine silvicultural regimes in the country have become more intensive with a typical regime including understorey vegetation management, wider tree spacing with lower initial stocking of *P. radiata*, and application of P fertiliser. These changes in management regime have created a need for more information on P dynamics in forest systems in order to create decision support systems to assist nutrient management.

The wider initial tree spacing creates potential for increased weed growth in forest stands through increased light and greater nutrient resources (Gadgil *et al.*, 1988; Payn *et al.*, 1998). Increased weed growth can compete with *P. radiata* for nutrients, water, and light, and many studies have shown that the growth rate of radiata pine is reduced by the presence of understorey vegetation (Squire, 1977; Nambiar and Zed, 1980; Mead *et al.*, 1993; Mead and Mansur, 1993; Clinton *et al.*, 1994; Richardson *et al.*, 1996; Watt *et al.*, 2003bc). This has led to intensive understorey vegetation management practices, with heavy emphasis on herbicide use in the establishment of *P. radiata* plantations in this country.

However, although understorey vegetation frequently causes harmful effects due to competition (antagonisms), interactions between some understorey species and *P. radiata* have been shown to provide beneficial effects to the tree. Richardson *et al.* (1996) demonstrated a positive interaction between *P. radiata* and weeds on P uptake by *P. radiata* in a field study. They reported that some species of grass, herbaceous broadleaves and buddleia significantly increased P concentration in needles of 3-year-old radiata pine trees, while broom, gorse, lotus and pampas had no effect on needle P concentration. However, they did not report the mechanism which caused the enhancement of needle P concentration.

Recently, Scott (2002) reported that there was an interaction between radiata pine seedlings and lucerne (*Medicago sativa* L.) in their effects on soil P dynamics, when they were grown together in a glasshouse trial. Soil P appeared to be depleted more under radiata pine seedlings grown with lucerne than under radiata, lucerne, ryegrass grown alone or when radiata was grown with ryegrass. He also found that when radiata seedlings were grown with lucerne, there was a significant redistribution of soil P from less labile to more labile fractions. However, issues to do with the experimental design make it difficult to draw firm conclusions from Scott's (2002) work.

A common feature in the studies of Richardson *et al.* (1996), Scott (2002), and many others (Squire, 1977; Nambiar and Zed, 1980; Gillespie and Pope, 1989; Gadgil *et al.*, 1992; Clinton *et al.*, 1994; Dolling, 1996; Miller *et al.*, 1998; Mason and Milne, 1999; Salam *et al.*, 2001; Gautam *et al.*, 2003; Watt *et al.*, 2003bc) was that although the overall effects of understorey vegetation on tree growth were quantified, it was not clear whether the interference between the plants was due to above-ground or below-ground competition and/or facilitation. The experimental designs used by these authors failed to make this distinction.

Phosphorus is an important nutrient in New Zealand forest plantations as most of the soils are P deficient or marginally deficient, and this element has been routinely applied since the 1960's where appropriate (Hunter *et al.*, 1991; Payn *et al.*, 1998). However, most of the information available on the P fertiliser requirements of radiata pine was

obtained from trials on first rotation forests that were managed under silvicultural regimes which were quite different from today. Nowadays, radiata pine forests in the country are mostly second rotation plantations with wider initial tree spacing and lower initial stocking of trees (400-800 trees ha^{-1}) compared to those prior to the 1990's (1200-2000 trees ha^{-1}). As noted earlier, such forest regimes have the potential for increased weed growth. Therefore, the response of radiata trees to P, and changes in P availability following P fertiliser application under wider tree spacing condition are expected to be more influenced by the interaction between the applied P fertiliser, the tree and understorey vegetation than has been the case in the past.

Many field trials in New Zealand have shown that direct application of reactive phosphate rocks (RPRs) to permanent pastures and crops, which have a long growing season and do not have short-term requirements for high levels of phosphate, can be as effective as single superphosphate (SSP) or triple superphosphate (TSP) (Mackay *et al.*, 1980; Gregg *et al.*, 1981; Mackay *et al.*, 1984; Gregg *et al.*, 1987, Harrison and Hedley, 1987; Bolan *et al.*, 1990; Smith *et al.*, 1990; Rajan *et al.*, 1994). Unlike for pastures and crops, few studies have been conducted on the direct application of phosphate rocks to radiata pine plantations in New Zealand especially on Pumice and Allophanic Soils (Mead, 1974; Mead and Gadgil, 1978; Hunter and Graham, 1983; Hunter and Hunter, 1991).

This thesis has focused on developing a better understanding of the interactions of P fertilisers, understorey vegetation and *P. radiata* on tree response to P fertiliser application and soil P chemistry. This information is expected to provide information for improvement of the P fertiliser Decision Support System (PDSS) currently being developed by Forest Research Institute of New Zealand. The PDSS allows one to identify appropriate management of understorey vegetation and P fertiliser in radiata pine plantations.

1.2 Objectives

The objectives of the thesis are:

1. To investigate the effect of different rates of two P fertilisers (Triple superphosphate (TSP) and Ben-Geurier phosphate rock (BGPR), and weed control and their interaction on soil P chemistry and the growth and the needle P concentration of 4-5-year-old second-rotation *P. radiata* trees in an Allophanic Soil and a Pumice Soil in the central North Island of New Zealand.
2. To compare the growth and P uptake of *P. radiata* seedlings when they are grown in pots with broom (*Cytisus scoparius* L.) or ryegrass (*Lolium multiflorum*) in an Allophanic Soil treated with different rates of TSP in a glasshouse trial.
3. To compare the rhizosphere properties of *P. radiata* when it is grown with broom or ryegrass in the above glasshouse trial.

Chapter 2

Literature Review

In this chapter, literature on the rate of growth and P uptake of *P. radiata* and understorey vegetation is firstly reviewed to compare the P removal from soil by these two vegetation types followed by a review of literature on P availability in forest soils and P fertiliser requirements of *P. radiata* in New Zealand. The last section of this chapter presents a review of literature on plant interferences and the effect of understorey vegetation on the growth and P uptake of *P. radiata.*

2.1 Growth rate of *P. radiata*

The above-ground biomass of *P. radiata* has been reported to increase at a slow rate from 1 to 3 years of age, followed by a fast rate from 3 to 12 years and again at a slow rate from the age of canopy closure around 13 years of age to 29 years (Madgwick *et al.*, 1977; Knight, 1978; Madgwick, 1985; Madgwick and Oliver, 1985; Madgwick *et al.*, 1988) (Figure 2.1). An average production rate of 15 tonnes ha^{-1} yr^{-1} for above-ground biomass of *P. radiata* from 2 to 22 years of age at a final-crop stocking rate of 540 stem ha^{-1} has been reported by Madgwick *et. al.* (1977) for first rotation plantations on Pumice Soils at Kaingaroa forest, in the central North Island of New Zealand. Meanwhile, Madgwick and Oliver (1985) estimated that the annual above-ground biomass production of first rotation *P. radiata* stands on Pumice Soils at the Long Mile area of Rotorua, from 5 to 13 years of age was 35.9 tonnes ha^{-1} yr^{-1}. The growth rate at the Long Mile area was approximately twice that at Kaingaroa forest because of much higher final-crop stocking rate in the forest at Long Mile (5190 stem ha^{-1}) than at Kaingaroa forest (540 stem ha^{-1}).

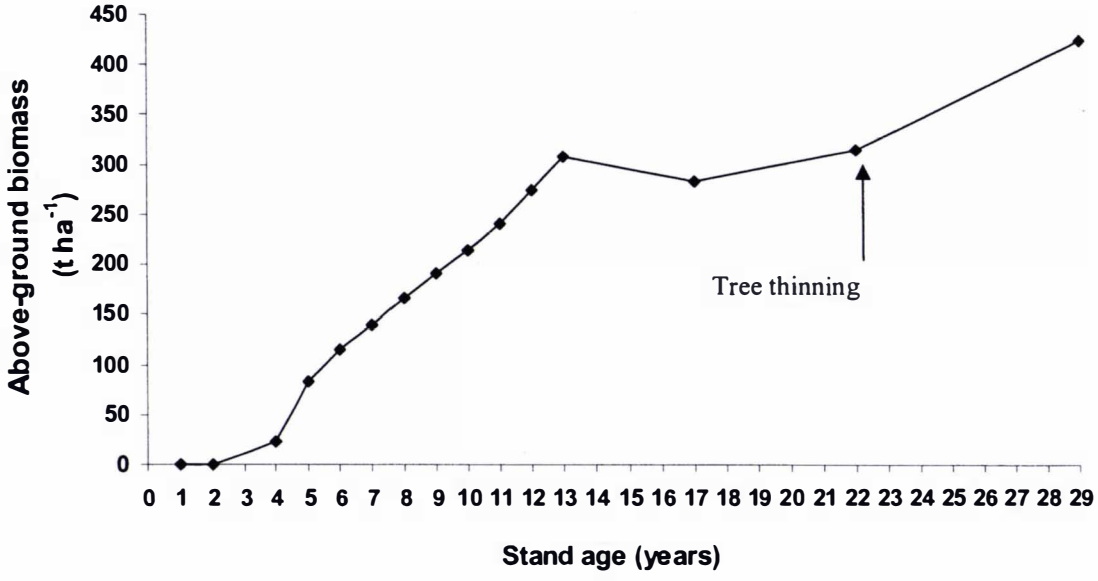

Figure 2.1 The above-ground biomass of *P. radiata* with increasing age (1 year, Knight, 1978; 2 to 4 years, Madgwick *et al.*, 1977; Madgwick, 1985; 5 to 13 years, Madgwick and Oliver, 1985; Madgwick *et al.*, 1988; 17 to 29, Madgwick *et al.*, 1977; Madgwick, 1985). Note that the data for different age groups are taken from sites with different agroecological conditions

2.2 Growth rate of understorey vegetation

Understorey biomass productivity in forest stands varies widely with tree species and age. Forrest and Ovington (1970) measured the above-ground biomass of understorey species (native grasses, bracken and broadleaved plants) under *P. radiata* stands with increasing age of the stands on a sandy loam soil at Billapaloola plantation, Tumut, New South Wales, Australia (Figure 2.2). They reported that following canopy closure (the ninth year) the grasses were completely absent and were replaced by bracken. Their results showed that during the third and fifth year of *P. radiata* the understorey biomass ranged from 46% to 82% of total above-ground forest biomass. This percentage

drastically declined (1.6% to 3.4%) beyond 5 to 8 years because of increased growth of *P. radiata* and decreased growth of understorey vegetation (Figure 2.2).

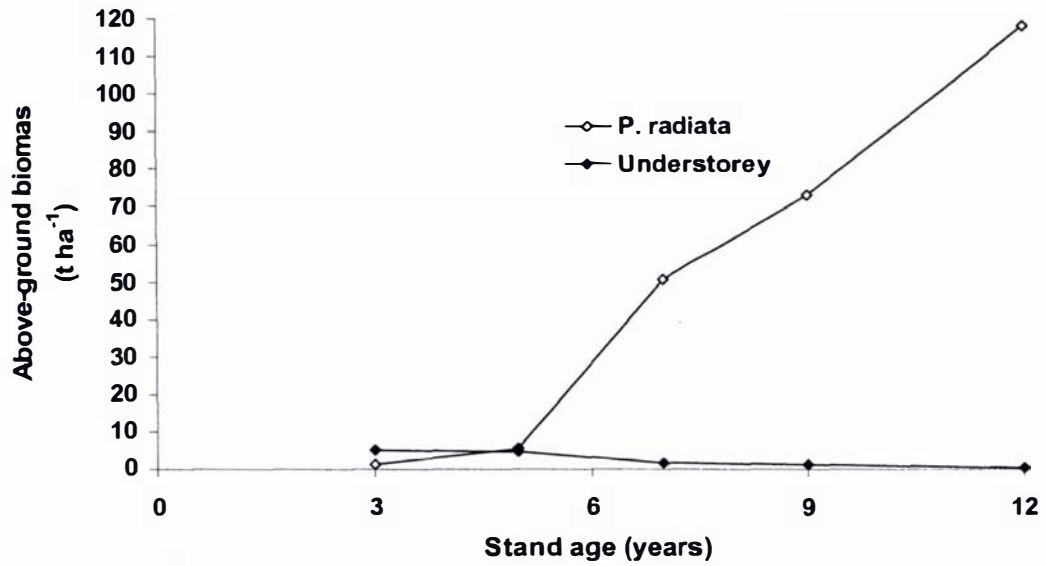

Figure 2.2 Above-ground biomass of understorey vegetation and *P. radiata* with increasing stand age (adapted from Forrest and Ovington, 1970)

Long and Turner (1975) also reported that the above-ground biomass of understorey decreased with increasing age of Douglas-fir stands (Figure 2.3). The understorey biomass (8 tonne ha^{-1}) in younger stands (22 to 30 year old) in this study was a significant fraction (12%) of the total above-ground forest biomass (65 tonne ha^{-1}) compared with the understorey biomass in older stands (3%) (3 and 211 tonne ha^{-1} for understorey vegetation and total biomass respectively when the trees were 73 year old).

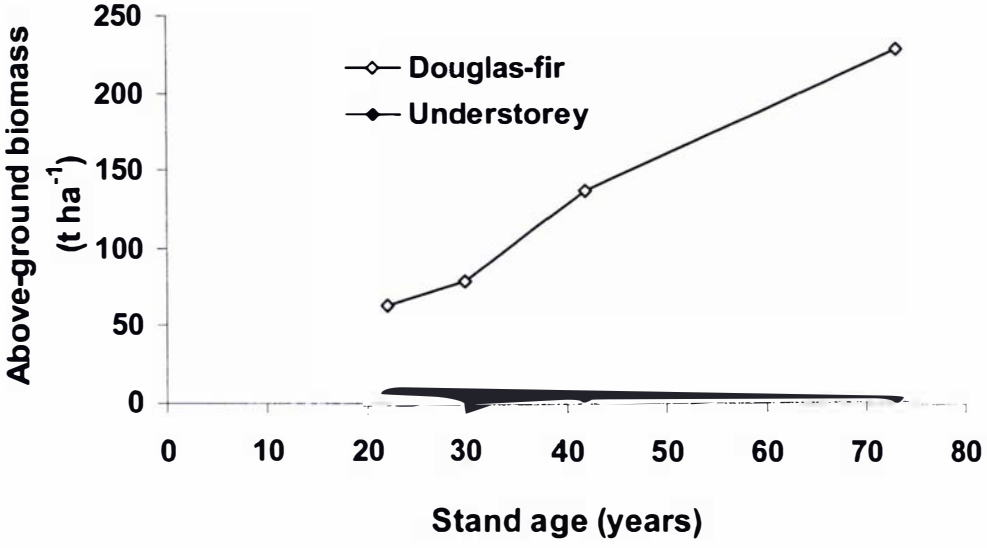

Figure 2.3 Above-ground biomass of understorey and Douglas-fir with increasing stand age (adapted from Long and Turner, 1975)

In *Eucalyptus diversicolor* stands, Grove and Malajczuk (1984) reported that understorey vegetation represented approximately 50% of the above-ground biomass in the 8- and 11-year-old stands, but 10% of biomass in the 4- and 36-year-old stands (Figure 2.4). They found that the important component of understorey vegetation in those stands was the legume *Bossiaea laidwiana*, which constituted 57% of the total understorey biomass in the 8-year-old stand.

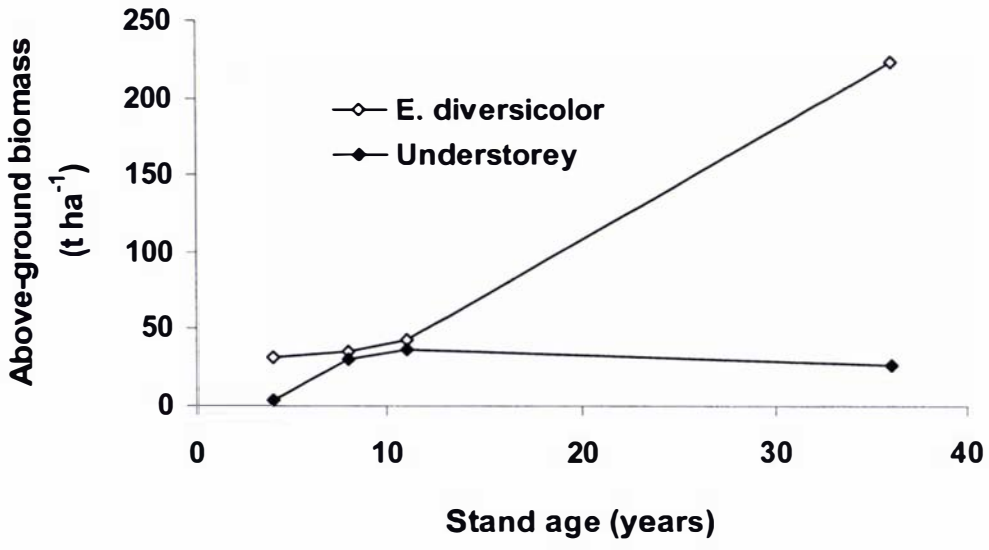

Figure 2.4 Above-ground biomass of understorey and *Eucalyptus diversicolor* F. Muell. stands with increasing stand age (adapted from Grove and Malajczuk, 1984)

The above-ground understorey biomass at Kaweka (Allophanic Soil) and Kinleith forests (Pumice Soil) in New Zealand (the forests used for the study reported in Chapters 3 and 4 in this thesis) under 4 to 5-year old second rotation *P. radiata* were measured to be 8.4 and 12.2 tonne ha^{-1}, respectively (A. Rivaie, unpublished data). The above-ground biomass of *P. radiata* was not measured in these forests. However, Beets and Pollock (1987) reported that the above-ground biomass of 4-year old *P. radiata* was 23.6 tonne ha^{-1} on a Pumice Soil at Puruki forest, New Zealand. Using these data the above-ground understorey biomass at Kaweka and Kinleith forests is estimated to be 26% and 38 % of the total above-ground biomass, respectively.

All the studies reviewed here showed that that the understorey biomass under conifers up to the age of canopy closure is a significant component of the total above-ground biomass, and in some cases it can be more than the conifer biomass.

2.3 P cycle in *P. radiata* forests

2.3.1 Introduction

Phosphorus (P) is a major essential nutrient that often controls plant growth and development in agricultural and forest ecosystems. In soils, P is supplied by parent material, branch/litterfall and fertiliser input. Therefore, the P status of a young undeveloped virgin soil is dependent primarily on the P content of the parent material, consisting of predominantly apatite, with some iron and aluminium phosphates in acid soils (Norrish and Rosser, 1983). This primary P is weathered through the action of climate and vegetation to give secondary inorganic mineral P, and inorganic P in soil solution. The inorganic P in soil solution is taken up by plants and soil microbes, or sorbed to become iron and aluminium phosphate minerals in acidic soils and calcium phosphate in calcareous soils (Syers and Walker, 1969ab; Williams and Walker, 1969a b; Adams and Walker, 1975; Walker and Syers, 1976; Cosgrove, 1977; Crews *et al.*, 1995) (Figure 2.5). Organic P in soils is mostly derived from plant residues by microbially mediated processes (Stewart and Tiessen, 1987). This organic P is a major component (34-71%) of total P in soils (Chen *et al.*, 2004), especially in *P. radiata* forest soils, and mineralisation of soil organic P is a major mechanism responsible for the enhancement of plant-available P (Davis and Lang, 1991).

In *P. radiata* plantations in New Zealand, Bray-2 P soil test values in the topsoil (0-10 cm depth) varies widely, ranging from 1.0 μg $P.g^{-1}$ (a Podzol Soil from Auckland) to 46.5 μg $P.g^{-1}$ (a Pumice Soil from Rotorua) (Skinner *et al.*, 1991) and total P ranges from 466 to 1300 μg $P.g^{-1}$ soil (Hunter and Hunter, 1991).

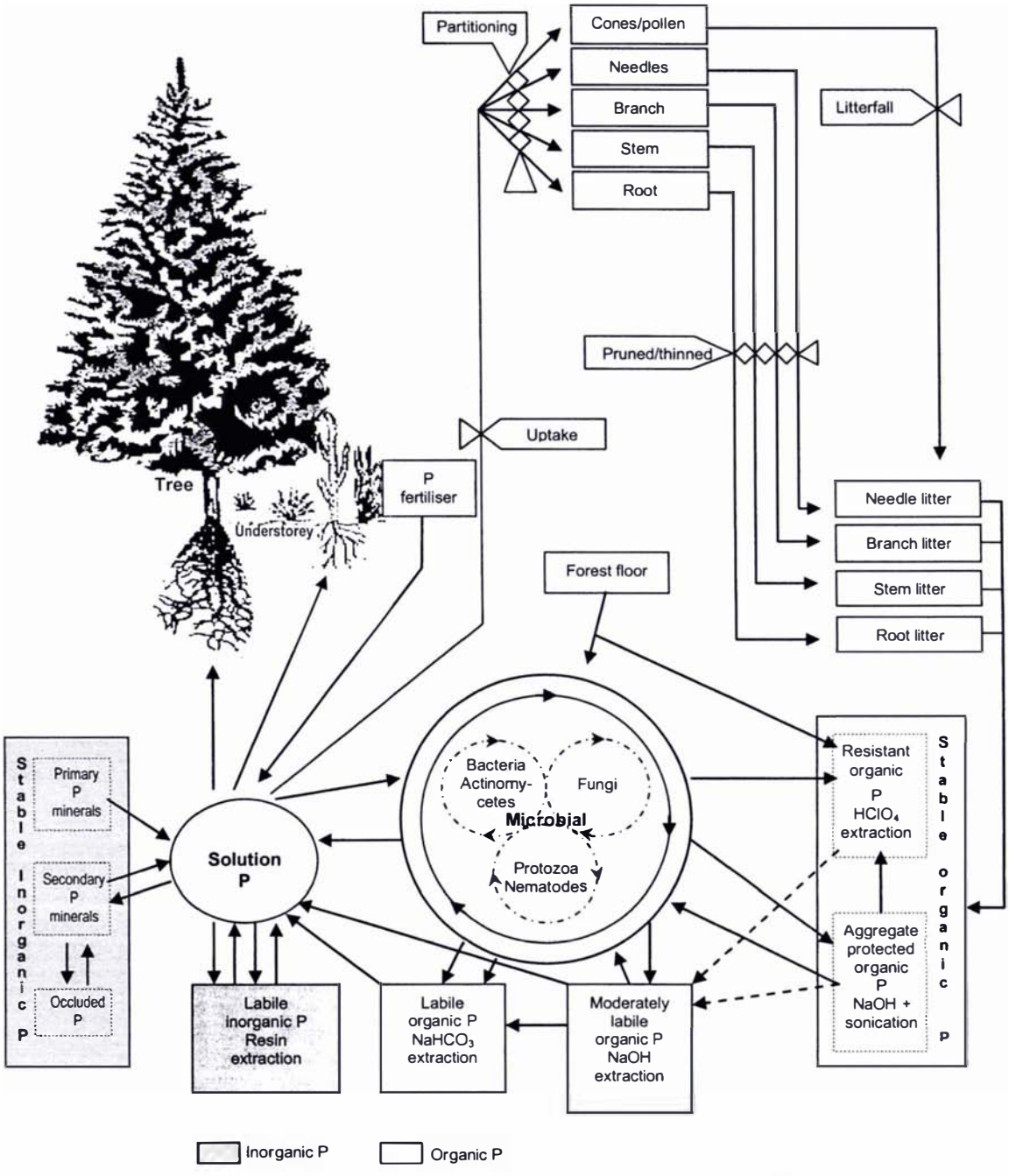

Figure 2.5 The P cycle in a *P. radiata* forest stand (adapted from Chauhan *et al.*, 1981; Mitchell, 2000)

Phosphorus in soil solution is taken up by the tree, understorey vegetation and soil microorganisms, or leached below the root zone. The P taken up by the tree is distributed into the various plant components depending on the requirements of these components (Figure 2.5).

Small amounts of P taken up by the tree are returned to the soil through litterfall/branchfall (3.4 kg P ha^{-1} $year^{-1}$) (Will, 1959) and from thinning/pruning or logging operations (40-55 kg P ha^{-1}) (Will, 1968). In addition, there is also a portion of the P taken up by the understorey vegetation returned to the soil as litterfall or after weed control operations prior to planting and post-planting, or after canopy closure (1-4 kg P ha^{-1}) (Parfitt *et al.*, 1994). Some P is removed from the cycle in the main stem during production thinning or logging (33 kg P ha^{-1}) (Will, 1968).

After decomposition, the litter from radiata trees and understorey vegetation releases P to soil solution. Meanwhile, P also enters the cycle through P fertiliser application, which constitutes a routine silvicultural operation in commercial forests managed intensively for high production (Figure 2.5). Fertilisers are commonly applied during planting (15 g P per seedling; 100 kg P ha^{-1}) and prior to canopy closure (100 to 110 kg P ha^{-1}), when the tree canopy is developing (Will, 1968; Madgwick *et al.*, 1977; Mead and Gadgil, 1978; Ballard, 1980; Skinner and Payn, 1993). The canopy closure occurs at 4 to 7 years, depending mainly on the stocking rate (Skinner and Payn, 1993).

2.3.2 Phosphorus content of above-ground biomass

In *P. radiata* plantations, P can exist in trees and in understorey vegetation. The relative proportion of P in the trees and understorey vegetation depends mainly on the age and spacing of the trees.

2.3.2.1 *P. radiata* biomass P content

The total P content of the above-ground tree biomass increases from 1 to 13 years of age. The rate of this increase is greater in the early years (2-6 years) than in the latter years (7-13 years) (Madgwick *et al.*, 1977; Knight, 1978; Madgwick, 1985; Madgwick and Oliver, 1985; Madgwick *et al.*, 1988) (Figure 2.6). The increasing P content of the tree is mainly due to an increase in the dry matter content of the tree (Madgwick *et al.*, 1977) (Figure 2.1).

Figure 2.6 The total P content of *P. radiata* with increasing stand age (1 year, Knight, 1978; 2 to 4 years, Madgwick *et al.*, 1977; Madgwick, 1985; 5 to 13 years, Madgwick and Oliver, 1985; Madgwick *et al.*, 1988; 17 to 29, Madgwick *et al.*, 1977; Madgwick, 1985). Note that the data for different age groups are taken from sites with different agroecological conditions

Will (1968) estimated that *P. radiata* stands on a Pumice Soil in the Kaingaroa forest, in the central North Island of New Zealand, removed approximately 41 kg P ha^{-1} from the soil during the first 10 years of growth. After this phase, during the next 25 years, the

amount of P taken up by the trees was only 11 kg P ha^{-1}. This led Will (1968) to suggest that the largest demand for P by the trees occurs prior to canopy closure.

The P uptake pattern of *P. radiata* trees from the time of planting was also reported by Madgwick *et al.* (1977). They reported that during the first 2 years after establishment the net annual P uptake of intensively managed *P. radiata* plantations on a good site in the north-eastern corner of the Kaingaroa forest was relatively low (1.5 kg P ha^{-1} yr^{-1}), while, between the second and fourth years after establishment the net annual P uptake was much higher (7.9 kg P ha^{-1} yr^{-1}) (Figure 2.7). They also suggested that between the second and the fourth years, the stand was closing its canopy rapidly. Therefore, the net annual P uptake decreases towards the end of this phase due to a steady-state nutrient cycle developing under closed canopy conditions. Meanwhile, Madgwick *et al.* (1988) suggested that at around 6 years of age, the maximum mean annual increment of P was attained. Thereafter, needle production decreased with stand age (from 7 years), and this decrease reduced the annual gross uptake of nutrients. Madgwick *et al.* (1977) also reported that in young stands, total P content increased at a relatively higher rate than the total biomass.

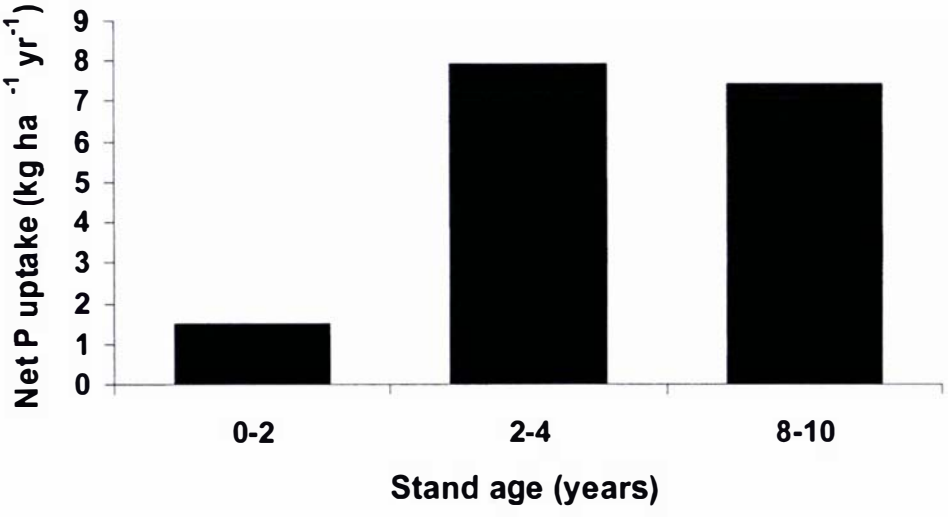

Figure 2.7 The net annual P uptake (kg ha^{-1} yr^{-1}) in the above-ground components of intensively managed *P. radiata* for selected growth periods (Madgwick *et al.*, 1977)

The relative quantities of P in the various components of the above-ground *P. radiata* trees changes with increasing age of the trees. Smith *et al.* (1994) studied the distribution of P in the various components of above-ground 5-year-old second-rotation *P. radiata* trees on sand dunes in the Woodhill forest, on the west coast of the North Island, New Zealand, where P was not limiting tree growth (needle P 0.14%) (Figure 2.8). They reported that the largest percentage of P (50.7%), within the aboveground components of the tree, was in the foliage.

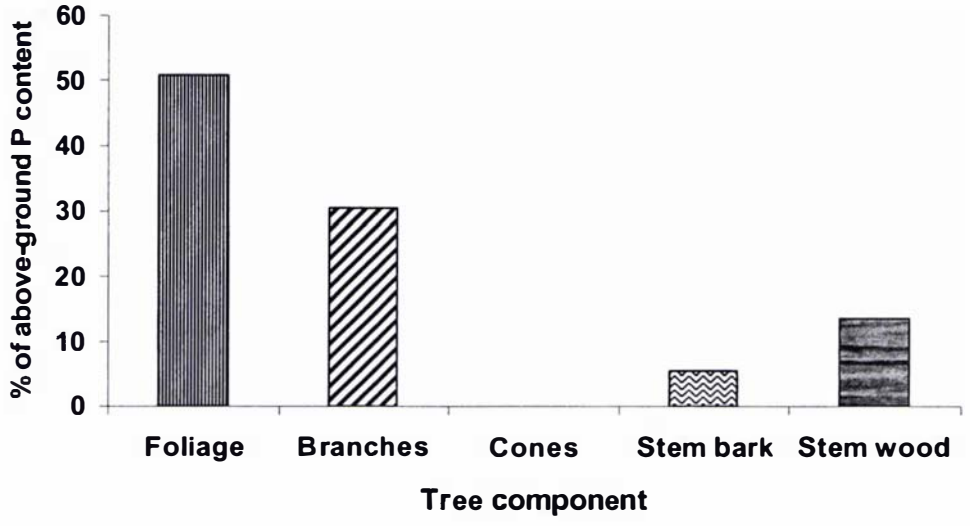

Figure 2.8 The P content of tree components as a percentage of total P content in the above-ground components of 5-year-old first rotation *P. radiata* trees (Smith *et al.*, 1994)

branches. The second largest portion of P (22.9%) was in the stem wood, as this component had the highest dry matter weight. Branches constitute a considerable portion (16.7%) of the P within the tree as well.

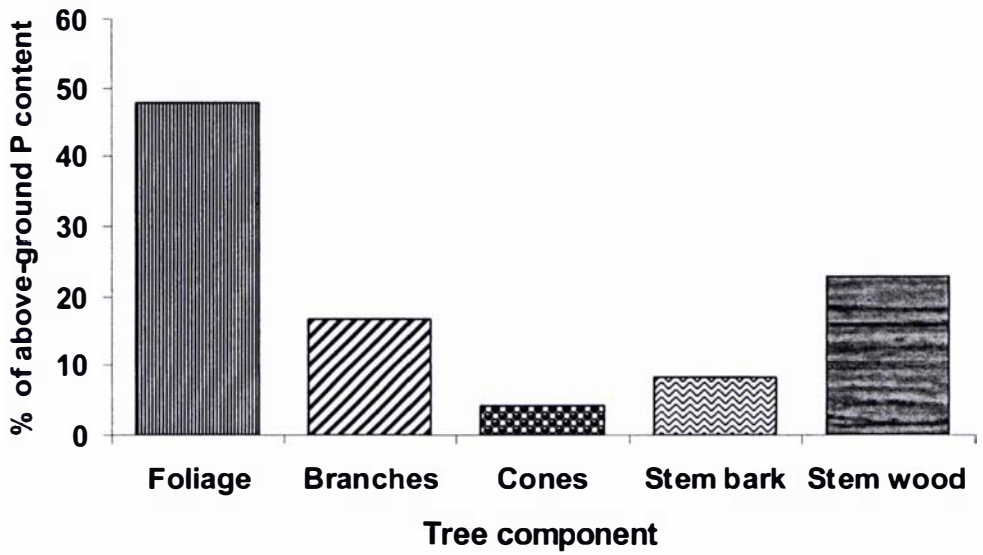

Figure 2.9 The P content of tree components as a percentage of total P content in the above-ground components of 8-year-old first rotation *P. radiata* trees (Frederick *et al.*, 1985)

Madgwick *et al.* (1988) also obtained similar results to Frederick *et al.* (1985) for P

biomass. Webber and Madgwick (1983) reported that the above-ground biomass P content of a 29-year-old *P. radiata* stand in Kaingaroa State Forest, which contained 426 tonnes dry matter ha^{-1}, was 66.3 kg P ha^{-1}. Of this, 20 kg P ha^{-1} (30.1%) was in the foliage, 9.5 kg P ha^{-1} (14.3%) was in the branches, 5.5 kg P ha^{-1} (8.3%) was in the cones, 7.4 kg P ha^{-1} (11.1%) was in the stem bark, and 24 kg P ha^{-1} (36.1%) was in the stem wood (Figure 2.10). These results show that approximately half the above ground P (47.2%) is removed from the ecosystem through stem harvest (Figure 2.10).

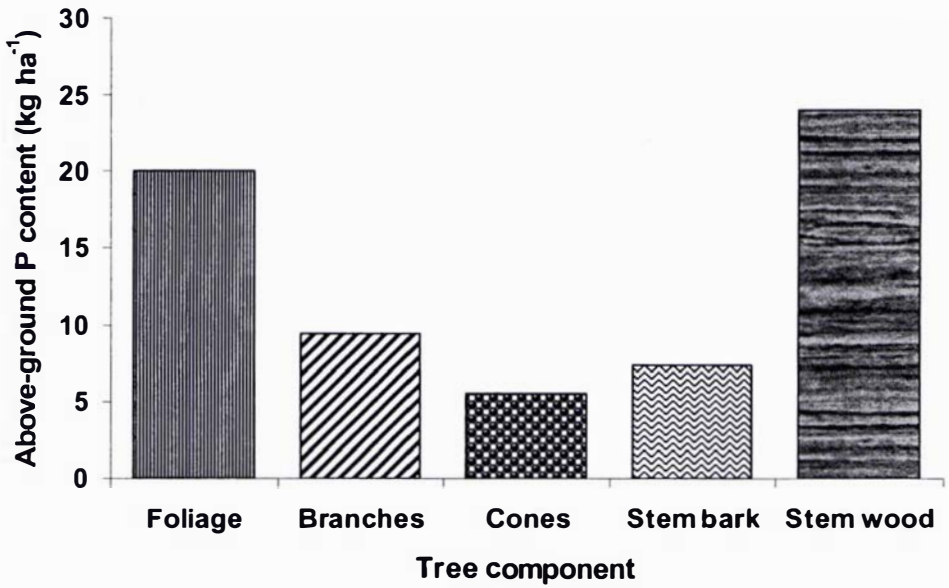

Figure 2.10 The P content of 29-year-old *P. radiata* tree components (Webber and Madgwick, 1983)

In addition to the tree age and spacing, soil P fertility influences the amount of P taken up by the tree. For example, Parfitt *et al.* (1994) reported that P uptake rates of 7-year-old closely-spaced *P. radiata* treated with 4 and 125 kg P ha^{-1} were 3.5 and 5.1 kg P ha^{-1} $year^{-1}$, respectively. In older trees, the P uptake rates of 11-year-old *P. radiata* treated with 25 and 100 kg P ha^{-1} were 6.0 and 8.1 kg P ha^{-1} $year^{-1}$, respectively.

2.3.2.2 Understorey biomass P content

The importance of understorey P in *P. radiata* plantations depends on a number of factors, including tree age and spacing. Parfitt *et al.* (1994) estimated that the P content of understorey vegetation under a 11-year-old radiata pine plantation on a Te Kopuru sand at Shenstone forest, in the South Island of New Zealand was 1 kg P ha^{-1}, whereas the P content of *P. radiata* was 27 kg P ha^{-1}, and the total P content of the ecosystem pools (understorey, pine tree and 0-15 cm soil depth containing LFH horizons) was 162 kg P ha^{-1}. Therefore, the P content of the understorey was only 3.6% of the P content in the above-ground biomass and 0.6% of the P content in the ecosystem pools. From the study of Parfitt *et al.* (1994), it appears that the understorey vegetation does not significantly contribute to the P cycling in the forest plantation when the trees are 11 years old. However, from the biomass data during the first 3-8 years of tree growth (see section 2.2), it appears that the P content of understorey vegetation could well be a significant proportion of the total above-ground P content, but no data on the relative P contents of the understorey vegetation and *P. radiata* trees for the first few years of tree growth are available in the literature.

Recently, in New Zealand second-rotation *P. radiata* forest plantations, there has been a steady trend towards wider tree spacing and lower initial stocking of *P. radiata*, and also an increased rate of application of P fertiliser (Payn *et al.*, 2000). These silvicultural practices are expected to increase the potential for weed growth through increased light and greater nutrient resources (Gadgil *et al.*, 1988).

Under wider-spaced trees, understorey vegetation would become a more significant component of P cycling in *P. radiata* forests than under closely-spaced stands,

especially before canopy closure is reached. For example, the P content of understorey vegetation under a 4-year-old second-rotation *P. radiata* stand on an Allophanic Soil at Kaweka forest ranged from 3.4 to 7.8 kg P ha^{-1} (at the stocking rate of 1000 stems ha^{-1}) (A. Rivaie, unpublished data) and the P content in the 4-year-old *P. radiata* was 16.5 kg P ha^{-1} (Madgwick, 1985). Therefore, the P content of understorey as a percentage of the total P content in above-ground biomass was 17 to 32%. These percentages are much higher than the 3.6% reported for understorey under an 11-year-old radiata stand (at the stocking rate of 1600 stems ha^{-1}) by Parfitt *et al.* (1994) and Hunter and Graham (1983).

2.4 Phosphorus forms in forest soils

Phosphorus supply to the plant is dependent on the total amount of P present in the soil, as well on the forms in which it exists. Soil P can be partitioned into two broad categories: inorganic (Al, Fe, and Ca-P) and organic P forms. The dynamics of P transformations in soils are controlled by chemical and biological processes (Khanna and Ulrich, 1984).

Phosphorus fractionation schemes quantify the amount of P in various labile and non-labile pools of forest soils. Phosphorus concentrations in these fractions can be determined by sequential soil P extractions using various chemical reagents (Chang and Jackson, 1957; Peterson and Corey, 1966; Williams *et al.*, 1967; Williams *et al.*, 1971; Bowman and Cole, 1978; Hedley *et al.*, 1982a; Condron and Goh, 1989).

Turner and Lambert (1985) studied the soil P fractions under 30-year-old *P. radiata* trees on Yellow Podzolic Soils at the Belanglo State Forest, Sydney, New South Wales, 30 years after different rates of superphosphate application (0, 25, 50, 75, and 100 kg P ha^{-1}), using a procedure that was similar to that used by Chang and Jackson (1957). They reported that increases in the rates of P applied significantly increased the concentration of NH_4F-extractable inorganic P (Al-P), but not the inorganic NH_4Cl-P (immediate plant-available P), NaOH-P (Fe-P), and H_2SO_4-P (Ca-P) fractions in the 0-7.5 cm soil depth. Of the inorganic P fractions, the concentrations of NH_4F- and NaOH-

extractable inorganic P (Al-P and Fe-P) were the highest. They also suggested that the organic P fraction, which was about 60% of the total soil P in all plots, might make a significant long-term contribution of P to the *P. radiata* stand.

2.4.1 Inorganic P

Plants take up inorganic P (P_i) directly from the soil solution (Anderson, 1980). The concentration of P found in the soil solution at any time is very small; approximately 0.1 to 1 μg P ml^{-1} in soils that have not been recently fertilised.

In acid soils, inorganic P reacts with free Fe and Al to form insoluble precipitates (Haynes, 1984). In addition, P is adsorbed onto the variable charged surfaces of oxides and hydrous oxides of iron and aluminium, and clay minerals (Saunders, 1965; Syers *et al.*, 1971). In calcareous soils, P usually accumulates as Ca bound P (Hedley *et al.*, 1982a; Tiessen *et al.*, 1983).

Precipitation-dissolution and sorption-desorption are abiotic processes, which are important in inorganic P transformations in soil. Kuo *et al.* (1988) suggested that desorption can be decreased by the presence of oxides of iron and aluminium, and an inverse relationship exists between desorbable P and P sorption capacity and the amount of sorptive sites unoccupied by P. The presence of low molecular weight organic acids, such as citric acid, or oxalic acid, can cause P to desorb by complexing metal ions such as Al, Fe and Ca, and releasing P bound to these metals (Bolan *et al.*, 1994; Bar-Yosef, 1996; Jones, 1998; Hinsinger, 2001).

Chen *et al.* (2000) reported that inorganic P was significantly higher (by 31%) in soils under a 19-year-old forest stand (mixture of *P. ponderosa* and *P. nigra*) on an Allophanic Brown Soil at the Craigieburn Research Area, in the central South Island, New Zealand than in adjacent areas under unimproved grassland, suggesting that changes in soil P dynamics and availability were related to the land-use change.

2.4.2 Organic P

In forest stands, labile organic P (P_o) fractions have been reported to be an important source for tree P nutrition (Kadeba and Boyle, 1978; Turner and Lambert, 1985; 1986; Adams *et al.*, 1989; Parfitt *et al.*, 1994). The concentration of P_o in the soil is controlled by the processes of immobilisation and mineralisation.

In New Zealand, it has been reported that P_o in the topsoil (0-10 cm) under conifer stands ranged from 25% to 63% of total P (Davis and Lang, 1991; Condron *et al.*, 1996; Chen *et al.*, 2000). Orthophosphate monoesters (accounting for 24-64% of the total P and 80-97% of the total organic P) were the predominant species of organic P in a soil under *P. radiata*, followed by much smaller quantities of orthophosphate diesters (<19% of organic P), and traces of phosphonates (Condron *et al.*, 1996; Chen *et al.*, 2004).

Phosphorus turnover through the microbial biomass and P_o mineralisation are important biological mechanisms that influence P_i release into the soil solution (Tarafdar and Claassen, 1988; Frossard *et al.*, 2000). In forest soils the release of P_i from P_o during decomposition of soil organic matter in the forest floor is an essential process in maintaining P supply. Biological and biochemical processes are involved in P_o mineralisation. The demand for energy of the soil microbial population facilitates mineralisation of P_o associated with soil C as a consequence of biological C mineralisation, whereas P-esters (independent of the main bulk of organic matter) are biochemically mineralised by extracellular enzymes, such as phosphatases (McGill and Cole, 1981; Magid *et al.*, 1996). These biological and biochemical processes take place predominantly in the rhizosphere soil where the microbial activity is higher than in the bulk soil (Bowen and Rovira, 1991; Junk *et al.*, 1993; Toal *et al.*, 2000; Chen *et al.*, 2002). In addition, other biological mechanisms can influence the availability of P in soil, such as root-induced pH changes and release of organic anions, and the development of specialised root structure, which are discussed in section 2.5.1.

Several studies have demonstrated that the concentration of organic P was significantly lower under conifers compared with adjacent grassland (Davis and Lang, 1991; Condron *et al.*, 1996; Davis, 1994; Chen *et al.*, 2000), suggesting that soil organic P mineralisation is induced by conifer roots.

2.5 Soil P availability to *P. radiata* trees

Phosphorus from the soil solution is taken up by plants directly either as the primary orthophosphate ion, $H_2PO_4^-$, or the secondary orthophosphate ion, $HPO_4^=$ (Anderson, 1980). There is no evidence that soil organic P (P_o) is directly available for plant uptake (Cosgrove, 1977). In soils, which have not been recently fertilised, the phosphate concentration in the solution at any time is approximately 0.1 to 1 $\mu g\ P.ml^{-1}$ (Larsen, 1967). Parfitt *et al.* (1997) reported that under 20-year-old *P. radiata* stands on Typic Orthic Brown soils, the concentration of orthophosphate in the soil solution was less than 0.031 $\mu g\ P.ml^{-1}$.

Phosphorus availability in soils is controlled by a combination of biotic processes (mineralisation–immobilisation) and abiotic processes (adsorption-desorption and dissolution-precipitation) (Frossard *et al.*, 2000). There have been many attempts to characterise soil plant-available P using water extraction (van der Pauw, 1971), quick chemical solution extractions such as Olsen P (Olsen *et al.*, 1954) and Bray P (Bray and Kurtz, 1945), anion exchange resin extraction (Sibbesen, 1978), isotopic exchange kinetics (Fardeau, 1996), and an infinite sink technique (van der Zee *et al.*, 1987).

Chemical extractants are used extensively to determine the plant-available P concentration, because methods using these extractants are rapid, and can be used for routine analysis. However, they are limited in their ability to accurately measure plant-available P as they are operationally defined by the chemical extractant used and also they only measure static P pools (Abrams and Jarrell, 1992). In addition, chemical extractants may mobilise P forms other than those that are truly plant available (Logan, 1982; Menon *et al.*, 1989).

The use of anion-exchange resins is a major methodological breakthrough in quantifying labile soil P (Qian and Schoenau, 2002) and may overcome some of the disadvantages of chemical extractions, such as mobilisation of P forms other than those that are truly plant available (Logan, 1982; Logan and Chaney, 1983; Menon *et al.*, 1989; Abrams and Jarrell, 1992). It has been reported that the amount of P extracted by anionic resins is well correlated to the amount of P uptake by plants (Bache and Rogers, 1970; Grigg, 1977; Sibbesen, 1978; Tran *et al.*, 1992; Saggar *et al.*, 1999) including *P. radiata* seedlings (Kadeba and Boyle, 1978). The use of anion-exchange resins *in situ* has practical advantages over conventional chemical extraction. The use of this method *in situ* minimises physical and chemical soil disturbances and is sensitive to on-site conditions such as the temporal and spatial variability in the field, thereby, giving more accurate information on soil P supply (Qian and Schoenau, 2002).

2.5.1 Phosphorus availability in the rhizosphere of *P. radiata* trees

The rhizosphere is the region immediately surrounding the plant roots. Therefore, P availability in this region should influence P uptake by *P. radiata* more than that in the bulk soils, which is further away from the roots. The width of the rhizosphere region extends a few mm to several cm from the root surface depending on plant species (Darrah, 1993; Bolan *et al.*, 1997). The rhizosphere of plants is the most chemically, biochemically and biologically active microsite in the soil (Tarafdar and Junk, 1987; Bowen and Rovira, 1991; Chen *et al.*, 2002). The properties of rhizosphere soil have been shown to be different from those of the bulk soil for many plants (Malajczuk and Cromack, 1982; Tarafdar and Jungk, 1987; Clarkson, 1985; Gahoonia *et al.*, 1992b; Darrah, 1993; Hedley *et al.*, 1994; Hinsinger and Gilkes, 1996; Chen *et al.*, 2002; Scott, 2002; Trolove *et al.*, 2003).

In conifers such as *P. radiata*, the roots are infected with ectomycorrhizae, which markedly influence the properties of the rhizosphere soils (Chen *et al.*, 2002; Scott, 2002; Liu *et al.*, 2004ab). The mechanisms involved in the nutrient uptake by the ectomycorrhizal root from the rhizosphere soil, especially P, are associated with: (i)

rhizosphere acidification (Gijsman, 1990ab; Haynes, 1990); (ii) nutrient depletion by plants; (iii) increase of the activities of soil enzymes (McGill and Cole, 1981; Tarafdar and Jungk, 1987; Gahoonia and Nielsen, 1992); (iv) excretion of root exudates (Hedley *et al.*, 1982a; Gardner *et al.*, 1983ab; Gerke and Jungk, 1991; Jones, 1998); and (v) specialised root structure (Gardner *et al.*, 1982).

The pH in the rhizosphere is affected by the balance of cation and anion uptake by the plant. The simultaneous uptake of several essential mineral nutrients in cationic (NH_4^+, Ca^{2+}, Mg^{2+}, K^+, Na^+ and most micronutrients) or anionic (NO_3^-, Cl^-, SO_4^{2-}, $H_2PO_4^-$) form in different proportions results in imbalance with respect to charge within the plant. In order to maintain electroneutrality within the plant cells, roots excrete charged ions back into the soil. When excess cations over anions are taken up by plants, roots generally excrete H^+, leading to a decrease in rhizosphere pH (rhizosphere acidification). Whereas, when excess anions over cations are taken up, roots generally excrete OH^- or HCO_3^- leading to a rise in rhizosphere pH (rhizosphere alkalisation) (Gijsman, 1990ab; Haynes, 1990). The excreted $H^+/OH^-/HCO_3^-$ is stoichimetrically equivalent to the charge imbalance (Breteler, 1973; Hedley *et al.*, 1982b; Troelstra *et al.*, 1985; Gijsman, 1990a).

There is evidence that rhizosphere pH changes are generally related to the proportion of NH_4^+ or NO_3^- uptake by plants (Bekele *et al.*, 1983; Darrah, 1993; Zoysa *et al.*, 1998). Gijsman (1990ab) reported that the pattern of pH changes in the rhizosphere of Douglas fir (*Pseudotsuga menziesii*) in strongly acid soil treated with NH_4^+, NO_3^- or a combination of both correlated well with the form of N taken up. The pH in the rhizosphere of Douglas fir decreased when the NH_4^+ form was used. When the NO_3^- form was used the pH in the rhizosphere increased, and when the combination of NH_4^+ and NO_3^- forms was used the pH in the rhizosphere increased slightly compared to the corresponding bulk soils. Olykan and Adams (1995) suggested that the decrease of pH in the rhizosphere soil of *P. radiata* seedlings was due to the plant taking up N predominantly in the form of cationic NH_4^+ rather than anionic NO_3^- from soil.

Some plant species have been reported to enhance P solubility by acidifying their rhizosphere when they were grown in P deficient soils (Riley and Barber, 1971; De Swart and Van Diest, 1987; Trolove *et al.*, 1996; Bolan *et al.*, 1994; Alfredsson *et al.*, 1998). Perrott *et al.* (1999) and Scott (2002) suggested that soil acidification in the rhizosphere was the reason for the depletion of Ca-P in the soil under *P. radiata* trees.

Furthermore, phosphatase enzymes released by plant roots have been demonstrated to hydrolyse P_o in the rhizosphere to P_i (McGill and Cole, 1981; Tarafdar and Jungk, 1987; Tarafdar and Claassen, 1988; Gahoonia and Nielsen, 1992b). This hydrolytic enzyme has been shown to hydrolyse P_o in the rhizosphere of slash pine (*Pinus elliottii*) (Trolove *et al.*, 2003).

Phosphorus deficiency in the soil may cause an increase in phosphatase activity resulting in increased hydrolysis of some of the labile P_o to produce inorganic P for plant utilisation, and thereby reduce P deficiency in the plant (Dracup *et al.*, 1984; Clarkson, 1985). The activity of this phosphatase enzyme has been shown to decrease with the addition of P fertiliser (Fox and Comerford, 1992a).

The activity of the phosphatase enzyme is higher in the rhizosphere of slash pine than in the bulk soil (Fox and Comerford, 1992a). Liu *et al.* (2004a) also found that increase of soil P availability in the rhizosphere of radiata pine was associated with increase in acid phosphatase activity.

Rhizosphere processes have been shown to increase the dissolution of sparingly soluble phosphate fertilisers such as phosphate rocks (Trolove *et al.*, 2003). Liu *et al.* (2004a) reported that the dissolution of Sechura phosphate rock applied to *P. radiata* seedlings in a P deficient Allophanic Soil was significantly higher in the rhizosphere soil than in the bulk soil. They explained that this was due to a significant increase in acidification, and oxalate produced by the roots in the rhizosphere soil. These root-induced processes resulted in an increase in the 0.1 M NaOH-P_i concentration in the rhizosphere soil compared to that in the bulk soil.

2.6 Phosphorus deficiency in New Zealand

In New Zealand, P deficiency in *P. radiata* was first recognised on clay soils at Riverhead State forest, north-west of Auckland, in the North Island in the early 1950s. In young trees, P deficiency can be recognised by short and yellow tipped needles at the end of branches. Meanwhile, in adult trees, P deficiency is noticed when needles are shed prematurely resulting in a thin crown (Figure 2.11). In more severe cases, leaders become spirelike – short branches with sparse short needles and from a distance, the colour and lack of foliage give a dull green to greyish-green appearance to the forest stand (Weston, 1956; Will, 1978).

Figure 2.11 Phosphorus-deficient radiata pine (tree in the middle), with narrow crown characteristic and needle fusion (picture taken at Kaweka forest, Hawke Bay, New Zealand)

It was found that tree growth in this forest increased considerably with the application of superphosphate at the rate of 2250 kg ha^{-1} to 20 to 24-year-old trees (Weston, 1956). Subsequently, P deficiency in radiata pine plantations has also been observed in many other clay soils of the Auckland region (Weston, 1956), and Hunter *et al.* (1991) reported that a large proportion of the forest plantations in New Zealand had various nutrient deficiencies, including P deficiency.

In the North Island of New Zealand, the most P-deficient soils are the highly weathered and leached clays developed from tertiary mudstones and sandstones in North Auckland and rhyolitic and andesitic parent materials in the Coromandel Peninsula (Gibbs, 1964; Will, 1978). Meanwhile, in the South Island, moderate levels of P deficiency occur in the more weathered and leached soils (Mapua and Rosedale hill soils derived from Moutere gravels and Kaiteriteri hill soils derived from granite) in the Nelson district

(Chittenden *et al.*, 1966). Moderate to severe P deficiency occurs in the Pakihi and related soils in Westland (Ballard, 1978; Mead and Gadgil, 1978). Various degrees of P deficiency can also be found in hill soils ranging from the Maramarua-King Country areas to the Rimutaka area close to Wellington, and in isolated areas in the eastern and southern parts of the South Island (Will, 1985).

2.7 Phosphate fertiliser requirement of *P. radiata* in New Zealand

Many studies in New Zealand have shown that P deficiency in *P. radiata* can be corrected through adequate P fertilisation (Appendix 1). Phosphorus fertiliser application to New Zealand plantation forests has traditionally been limited to correcting overt P deficiency, rather than maximising wood production (Payn *et al.*, 1998). The rate of P fertiliser required for maximising wood production is much higher than that required for correcting overt P deficiency (Ballard, 1977; Ozanne, 1980; Bevege, 1984; Skinner *et al.*, 1998).

In 1997, New Zealand had approximately 1.5 million ha of plantation forest, 95% of which was in *P. radiata.* In the same year it was estimated that 350 tonnes of P was applied to the plantation forests (Payn *et al.*, 1998; 2000). 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 would need to be twice the current amount (350 tonnes) just to remove acute P deficiency; and would need to increase by five times in order to maintain current soil P level. It would need to increase by about ten times if the desire was to maximise wood production (Payn *et al.*, 1998).

In New Zealand, the commercial application of fertilisers to exotic forest began in the Auckland region during the late 1950s where most areas of *P. radiata* stands were found to be severely P-deficient (Mead and Gadgil, 1978). Weston (1956; 1958) reported that the earliest successful P fertiliser trials were laid down in 1952 at

Riverhead State Forest, northwest of Auckland on a Podzol Soil. These trials showed that 225 kg P ha^{-1} applied as a mixture of superphosphate and other P fertilisers (75% superphosphate, 15% ground Nauru rock phosphate, and 10% ground serpentine rock) considerably increased the mean height and volume of the *P. radiata* trees 24 years after fertiliser application. He reported that the average predominant mean heights of the trees on soils treated with 0 and 225 kg P ha^{-1} were 19.5 and 33.1 m, and the stand volumes for these treatments were 206 and 981 m^3 ha^{-1}, respectively. Subsequent to these trials, several new trials were laid down in many parts of New Zealand. The summary of the results from these trials is presented in Appendix 1.

Superphosphate was the main source of P fertiliser used in New Zealand until the late 1970s (Skinner and Payn, 1993). Will (1981) reported that in New Zealand during 1980, superphosphate constituted 67% of the 1140 tonnes of P applied to the forest stands, while diammonium phosphate and other sources constituted the remainder.

In the late 1960's and 1970's, there were two series of trials, AK286 (Appendix 1, no. 11- 14) and AK734 (Appendix 1, no.16-18) conducted on *P. radiata* to determine the optimum rates of P application. The AK286 series examined rates of application of P as superphosphate (Mead and Gadgil, 1978), and the AK734 series tested rates of P as either superphosphate or rock phosphate (Hunter and Graham, 1982). 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 plantations. In 1998, the entire AK286 series of trials were completed. The information from this series has been used to determine the relationship between needle P concentration and productivity (Payn *et al.*, 2000).

Subsequent to the AK series trials, a trial was set-up in 1978 to compare the effectiveness of superphosphate and three rock phosphates ("A" and "C" grade phosphate rocks, and "citraphos" from Christmas Island) applied at the rates of 0, 75, and 150 kg P ha^{-1} to 4- to 7-year-old first rotation stands on three P deficient soils (Bray P 1-2 μg P g^{-1} soil) of contrasting P retention capacities (P retention 93%, 48%, and 0%; soil pH 5.4, 4.9, and 4.5, respectively) at Tairua State Forest, Riverhead State

Forest, and Waipoua State Forest, in the North Island of New Zealand. The results showed that three years after P application, the effectiveness of the fertilisers in increasing needle P concentration in all three soils decreased with decreasing 2% citric acid solubilities of these fertilisers in the order, superphosphate ≥ A grade rock ≥ citraphos > C grade rock (Hunter and Graham, 1983).

In mid-1988, another trial was commenced to study the effect of phosphoric acid acidulation of a phosphate rock (0, 20, 25, 30, and 100% acidulation) on P nutrition of second-rotation radiata pine at Riverhead forest on Waikare Clay soil, with medium P retention (48%). The fertilisers were applied at rates of 25, 50, and 75 kg P ha^{-1}. The results showed that 5 years after P application there was significantly different forest productivity gains (basal area) between P treated plots and control plots (Skinner *et al.*, 1998). But there was no difference in tree basal area among P rates and forms. Needle P concentration for 50 and 75 kg P ha^{-1} treatments were at or above the critical level of 0.11%, and for the 25 kg P ha^{-1} treatment, it was approximately 0.10%, whereas for the control treatment it was 0.08%. Skinner *et al.* (1998) suggested that satisfactory radiata growth gains can be achieved with any form of P fertiliser application at rates between 25 and 50 kg P ha^{-1}. Reactive phosphate rock (RPR) which is cheaper than the other P sources has, therefore, been recommended in New Zealand as the P fertiliser source to correct P deficiency in *P. radiata* stands (Payn *et al.*, 1998).

Most of the trials conducted up to the mid-1990s have been on first rotation plantations. There is little information available on the effect of P fertiliser (water soluble and/or water insoluble) application on second rotation plantations.

2.8 Phosphate decision support system (PDSS)

Recently, based on the results of the long-term P fertiliser trials (AK286 and AK734 series), *P. radiata* responses to P fertilisers have been modelled and mathematical functions developed. Foliar P responses to P fertiliser rates in the series of trials are shown in Figure 2.12.

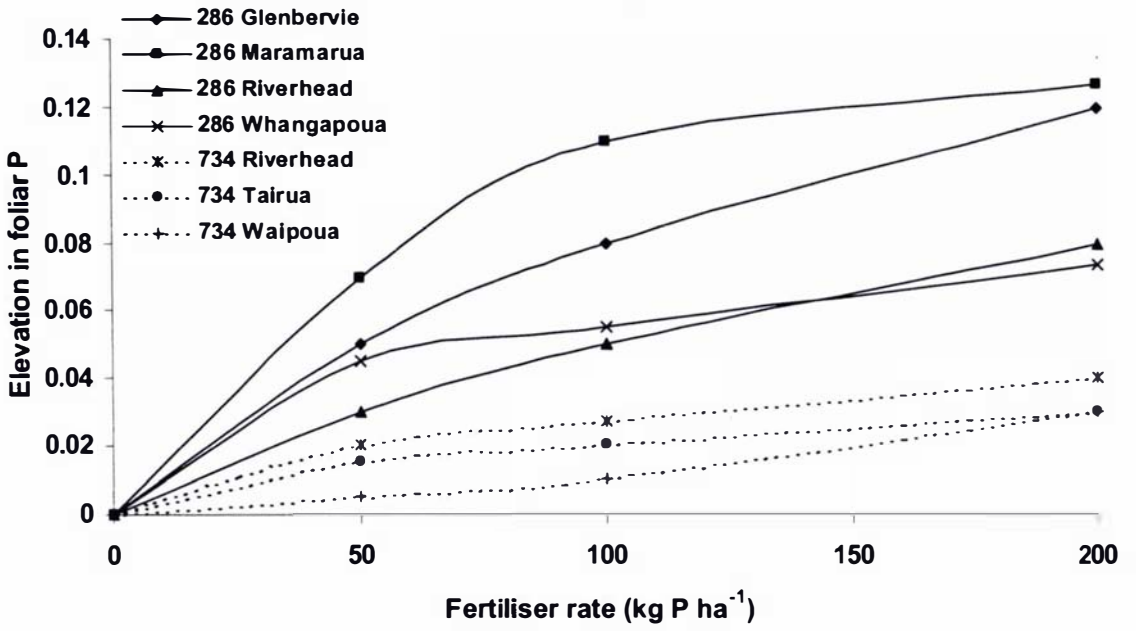

Figure 2.12 The foliar P response to P fertiliser rates (adapted from Skinner *et al.*, 1998)

Attempts have been made to incorporate these mathematical functions into a Phosphate Decision Support System (PDSS) (Skinner *et al.*, 1998) (Figure 2.13). With further improvements and field scale validation of this system, forest managers will be able to use this system to predict *P. radiata* growth response to foliage and soil P status as well as to determine tree growth response to the various types and rates of P fertiliser applied.

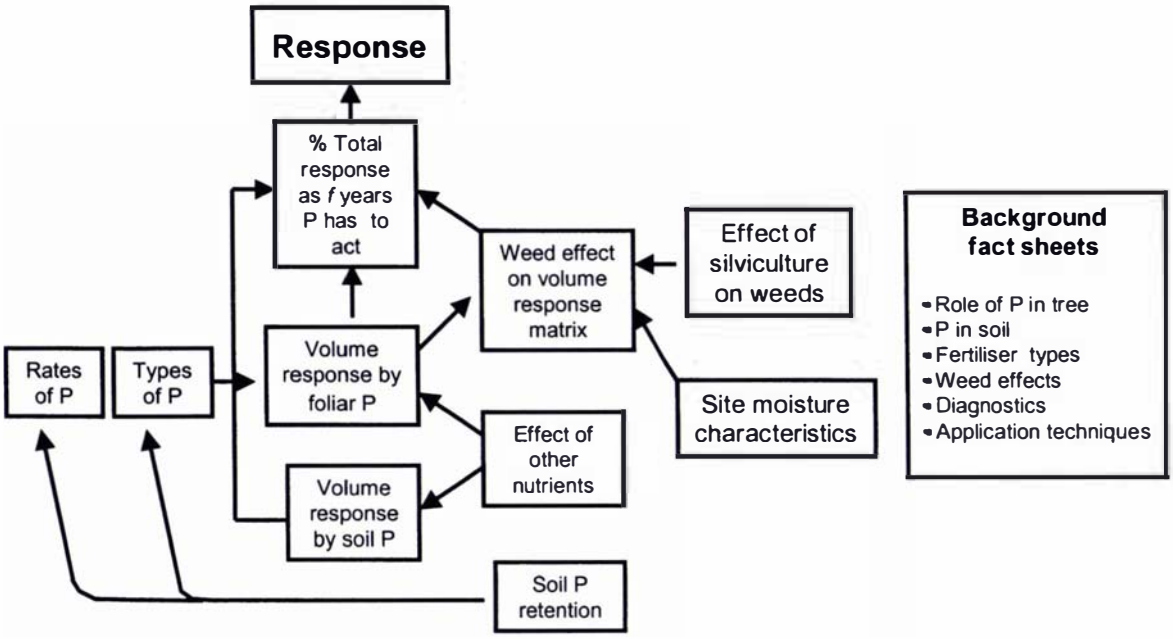

Figure 2.13 The conceptual model for the PDSS (adapted from Skinner *et al.*, 1998)

The PDSS has provision for the weed effects, but as yet there are no data available on this. In a second rotation *P. radiata* forest, with wider spacing, weeds are likely to be more important than in the first rotation. MacLaren (1993) suggested that in the second-rotation of *P. radiata* plantations, weed growth was often higher than in the first-rotation sites. He explained that this was because the dormant seeds of weeds at the end of the first-rotation would germinate due to soil disturbances during logging, and also as a result of increased light availability. In addition, perturbations imposed by the use of heavy equipment during logging operation and the deposition of harvesting slash may also facilitate the establishment of weed species (Luken *et al.*, 1997). With higher weed growth under trees, weeds may have influence on the P fertiliser response by the trees. Therefore, the weed factor is also included as a component in the PDSS (Figure 2.13), but no data on this aspect is currently available.

The two trial series used in the PDSS (AK286 and AK734) had a higher initial stocking rate (1200-2000 stems ha^{-1}) and narrower tree spacing than what is practiced today

(400-1000 stems ha^{-1}). At lower stocking rates, the tree-spacing is wider and this is expected to produce higher weed growth. Therefore, in forests having trees with a lower stocking rate, the weed effect on the response of trees to P fertiliser would be greater.

The significance of weeds in forest stands, especially their role in enhancing or reducing P availability to forest trees, is presented in the next section.

2.9 Plant interference

In nature, plants usually grow in association with other plants of the same or differing species - they rarely exist in isolation. In this association, plants may interact in a number of ways to meet their demands. Interference is the effect that the presence of a plant has on the growth or development of its neighbors. It is the general term used for describing "interactions among species, or populations within a species, which can be expressed as an alteration in growth rate or form which results from a change in the plant's environment due to the presence of another plant" (Hall, 1974; Radosevich *et al.*, 1997).

A plant (or any other organism) is an important participant in effecting change on its environment. It may affect the environment in a negative way in relation to other plants or organisms (for instance, low nutrient or water uptake, allelochemical production, etc.). This is called *competition or antagonism.* On the other hand, a plant may affect the environment in a positive way (Vandermeer, 1989), such as enhancement of N availability by N_2-fixing species in forest ecosystems (Bormann and DeBell, 1981; Zou *et al.*, 1995) or increased P availability in the soil beneath or near conifers for utilisation by other plant species (Fisher and Stone, 1969; Condron *et al.*, 1996). This interaction is called *facilitation* (positive interference) (Vandermeer, 1989). Another name for this type of interaction is *synergism.*

2.9.1 Negative interference (antagonism)

There are three possible negative interferences (antagonisms) that can occur among plant species growing close to each other, namely competition, amensalism, and parasitism (Burkholder, 1952).

The definition of competition is "a negative interaction between individuals brought about by a shared requirement for resource in limited supply, and leading to reduced growth, reproduction, and/or survival of one or more individuals concerned" (Begon *et al.* 1986). Suppression of *P. radiata* tree growth as a result of competition for nutrients and water between pasture and *P. radiata* trees in the forest community is an example of competition (Squire, 1977; Nambiar and Zed, 1980; Clinton *et al.,* 1994; Richardson *et al.*, 1993; 1996; 2002).

Amensalism is defined by Barbour *et al.* (1987) as the mutually adverse effects of organisms (plants) that utilise a resource in short supply in which only one of the plants is affected, whereas the other plant remains stable. In this type of negative interaction, a dramatic decrease in plant biomass or an increase in mortality is usually evident for one plant species but not for the other (Radosevich *et al.*, 1997). One form of amensalism is allelopathy. Allelopathy is defined as the detrimental effect of one plant on another by the production of a harmful chemical (Nye and Tinker, 1977). Allelochemical substances may be present in leaves, flowers, fruits, roots, rhizomes, and seeds. The effect of this chemical often may result in obvious and startling responses in affected plants, for instance, the failure of germination or sudden death of herbaceous plants growing near black walnut (*Juglans nigra* L.) due to a chemical (juglone) produced in the leaves and roots of the walnut tree (Radosevich *et al.*, 1997).

Another example of amensalism may be the dramatic reduction of 3- year-old *P. radiata* stem volume in the presence of buddleia and pampas and the significant increase of tree mortality due to the presence of buddleia (by 14%) and pampas (by 9%) under *P. radiata* stands (Richardson *et al.*, 1996). They suggested that the most probable explanation for the large weed effect on tree growth was the restriction of light.

However, it was not known whether *P. radiata* also affected the growth of buddleia and pampas, because there was no plot with only weeds in their trial. If the weeds were also affected by restriction of light caused by *P. radiata*, then this interference falls in the category of competition rather than amensalism.

When a plant or animal living in, on, or with another living organism at whose expense it obtains food, shelter, or support then it is called a parasite. Parasites may be surviving only in association with the living host (obligate), or living either saprophytically or on a living host (non-obligate). Some parasitic flowering plants even have chlorophyll, but they still rely on the host plants for water and nutrients. Parasitic weeds, such as dodders, mistletoes, broomrapes, or witchweeds, are major important weeds under agricultural crops or forest trees (Radosevich *et al.*, 1997).

2.9.2 Positive interference (synergism)

Many theories have been proposed to explain positive interference (synergism) among plants influencing plant distributions, productivity, diversity, and reproduction (DeAngelis *et al.*, 1986; Hunter & Aarssen, 1988; Vandermeer, 1989). Commensalism, protocooperation, and mutualism are forms of positive interference. Commensalism is a one way relationship between two plants in which one plant is benefited without any harm occurring to the other and without itself being affected. When the two plants in a relationship are stimulated by the interference (benefiting both plants) but unaffected by its absence, this positive interference is called protocooperation. Meanwhile, in a mutualistic relationship both plants are benefited and are mutually dependent (Radosevich *et al.*, 1997).

Facilitation may be thought of as a positive ecological process (Radosevich *et al.*, 1997). In positive interference, plants may provide direct facilitation by ameliorating harsh environmental characteristics, changing substrate characteristics, or increasing the availability of a resource; or may provide indirect facilitation by eliminating potential competitors (Connell, 1990; Miller, 1994; Callaway, 1995), influencing the abundance

of other beneficial organisms such as bacteria and mycorrhizae in the rhizosphere, providing pollinators, or protecting from herbivores (Trenbath, 1976; Hunter and Aarssen, 1988; Callaway, 1995).

Facilitation and competition may operate simultaneously between neighboring plant species when resource demands exceed the supply (Hunter and Aarssen, 1988; Radosevich *et al.*, 1997; Zhang and Li, 2003). The lack of appropriate methods to study positive interactions occurring below-ground have made it difficult to understand the mechanism causing the positive interaction (Hunter and Aarssen, 1988).

Plants through their physical presence and physiological activities may change their microclimate circumstances, such as temperature, wind flow, light intensity/quality, or water availability (Hunter and Aarssen, 1988). For example, soil water availability under *Quercus rotundifolia* and *Q. suber* in Spanish savannas was greater than in soils in the open and this condition was followed by large differences in plant species composition between and under the trees, as against in the open (Joffre and Rambal, 1988).

Some studies have demonstrated that deep-rooted perennial trees may take up soil nutrients from the deeper soil layers and return them to the soil surface via litterfall and throughfall. This "nutrient pumping" mechanism (Richards and Caldwell, 1987) results in higher nutrient concentration in the surface soil layers beneath the tree than in the adjacent soil (Fisher and Stone, 1969; Gillespie and Pope, 1989; Davis and Lang, 1991; Zou *et al.*, 1995; Condron *et al.*, 1996; Binkley *et al.*, 2000). Like the perennial trees, the presence of deep-rooted understorey vegetation in a forest stand may have a positive effect on the trees by altering soil nutrient composition through this "nutrient pumping" mechanism.

2.9.3 Experimental techniques in studying plant interference

To date, considerable research on plant interference has been carried out. However, the experimental designs used in these studies vary from one study to another, and from species to species depending on the aims, objectives and practicalities of the studies, thus there is no optimum design for competition experiments (Freckleton and Watkinson, 2000). Evidence for negative interference has been examined through competition studies over the last three decades (Strong *et al.*, 1984; Hunter and Aarssen, 1988), whereas, evidence for positive interference, especially below-ground is relatively scarce due to methodological difficulties (Hunter and Aarssen, 1988).

There are several experimental designs most commonly employed for examining plant interference. They can be grouped under: (1) monocultures, (2) replacement series, (3) additive series, and (4) addition series (bivariate factorial design).

In the monoculture approach the performance of individual species grown in monocultures is used to predict the performance of mixtures of species. This theory is based on the assumption that interspecific interference is consumer-resource based, and that the competitive ability of a plant species depends on various plant traits, such as relative growth rate, minimal tissue nutrient concentration required for plant growth, and proportion of biomass in the root (Tilman, 1990). The increase in plant densities in monocultures can be used to study the severity of intraspecific competition between plants. The plants will be more severely affected when the plant densities increase, thus, the mean size of surviving plants will decrease. However, interference between plants is often very complex (Firbank and Watkinson, 1990; Pannell, 1993). For example, in a mixture, compared with single plant species, one species will have different resource requirements and different growth patterns than the other. They will modify the environment of each other (Firbank and Watkinson, 1990). In addition, there is also a possibility of non-competitive allelopathic interference between plants in mixures (Newman and Rovira, 1975; Pannell, 1993). These make the performance of a species in a mixture not always accurately predictable from its performance in monocultures (Harper, 1977; Austin *et al.*, 1985; Grace, 1988).

In replacement series designs the proportion of species within mixtures is varied at a constant total density (Freckleton and Watkinson, 2000) by replacing individuals of a monoculture of a first component by individuals of a second component until a monoculture of the second component is achieved (Harper, 1977). Because of its simplicity, this design is commonly employed (Law and Watkinson, 1987; Freckleton and Watkinson, 2000). The results can be described using easily-calculated indices, such as relative yields and relative crowding coefficients (Hall, 1974; Harper, 1977). This design has been proven to be valuable for studying the effects of single factors on the outcome of interference between two species (Firbank and Watkinson, 1990). However, the replacement series has been severely criticised because the design confounds the effects of intra- and interspecific interference (Law and Watkinson, 1987), the results are density dependent (Firbank and Watkinson, 1990; Snaydon, 1991), and there are problems with analysis and interpretation of the coefficients (Law and Watkinson, 1987).

The additive series design is also simple where plants are grown either with or without competitors and competition is treated in a factorial manner (Freckleton and Watkinson, 2000). Silvertown and Doust (1993) suggested that the additive series design was suitable for studying the effect of weed infestation on a crop planted at fixed density. In additive series design the effects of intra- and interspecific interference are not separated and the experimental results are affected by the changes in plant density (Freckleton and Watkinson, 1999), thus, this design has attracted much criticism (Freckleton and Watkinson, 2000).

In additive series design the effects of different combinations of densities and frequencies are not considered. Snaydon (1991) has proposed an addition series or a bivariate factorial design to include these variables. In this design, mixtures of plants with a range of densities and proportions are studied. The results can be analysed as an additive mixture, having measures of competitive ability, resource complementarity, and severity of competition (Snaydon, 1991). One of the criticisms of this design is that it has a large number of treatments, which makes the experiment too big to conduct.

Donald (1958) developed a technique using panels in pot experiment to divide plant competition into components relating to the above-ground and below-ground competitions. He placed separating panels between plants, above and/or below the soil, thus the plants were grown under conditions of no competition, below-ground competition only and, above-ground competition only. He also had a treatment with no separating panels to cause both below- and above-ground competition. However, many studies have shown that above-ground competition may affect a plant's below-ground competitive ability or vice versa (Belcher *et al.*, 1995; Twolan-Strutt and Keddy, 1996). Moreover, the aerial partitions could affect the plant environment by altering the air-flow or the radiation-climate (Warren and Lill, 1975), thus encouraging the growth of a more aggressive species and suppressing that of less aggressive species (Yamada, 1985). Meanwhile, below-ground partitions not only prevent intermingling of roots of the plants which are separated by the partition but also divide the soil resources and space for roots to spread (Pannell, 1993). In this case, the soil volume per plant must be held constant to eliminate the confounding effect of treatments with plant root density (Groves and Williams, 1975; Pannel, 1993).

Pannel (1993) studied the effects of root interference on P uptake by browntop (*Agrostis capillaris*) and white clover (*Trifolium repens*) using a dual radioactive P labelling technique. The basis of the design was to determine the relative amounts of P that a row of plants (either browntop or white clover) can absorb from two adjacent soil spaces, one predominated by white clover roots and the other by browntop roots. She found that browntop consistently acquired more radioactive P from soil space shared with white clover roots than with roots of other browntop plants. At the lowest level of P supply tested, white clover acquired less radioactive P from the soil space shared with browntop than with other white clover plants. This was explained as being due to higher competition by the browntop than clover for P uptake. At high levels of P supply, white clover had a greater uptake of P from soil space shared with browntop than with other white clover plants. This was explained to be due to intraspecific competition between white clover plants being greater than interspecific competition with browntop plants.

The dual labelling technique used in this trial of Pannell (1993) gave only a "snapshot" picture of the effects of root interferences occurring between roots of browntop and white clover on P uptake in an established sward at the time of applying the isotope. A criticism of this method is that it did not give any indication of the effect of the two species on the total P uptake of each other over their whole life span which can be determined from the more traditional types of plant competition trials (Pannell, 1993). Also, the root density of browntop measured in the trial was substantially lower than that found in the field and, therefore, the results cannot be used to explain field observations. In the field, the mat forming behaviour of browntop, physically impeding the growth of white clover and shading white clover stolons, would reduce the severity of competition for soil P between the roots of these plants.

Using below-ground partitions in pots, Scott (2002) showed that interference between roots of *P. radiata* seedlings and lucerne (*Medicago sativa* L.) changed soil P fractions compared to when the seedlings were grown alone. However, the design in his study failed to keep the soil volume per plant constant, as the pots containing seedlings alone had a higher soil volume per plant than that of the mixture of seedlings and lucerne.

2.10 The role of understorey vegetation in nutrient cycling under forest stands

Understorey vegetation control operations using herbicides are common in the establishment of *P. radiata* plantations in New Zealand, and these operations usually result in a considerable increase in tree growth (Richardson *et al.*, 1993; 1996). These practices are recommended because many studies have shown that the growth rate and survival of the trees is reduced in the presence of understorey vegetation. This is probably due to the competition of understorey vegetation with *P. radiata* for water, nutrients and light (Squire, 1977; Nambiar and Zed, 1980; Gadgil *et al.*, 1992; Clinton *et al.*, 1994; Richardson *et al.*, 1996; Mason and Milne, 1999; Watt *et al.*, 2003bc).

On the other hand, several other studies have suggested that understorey vegetation may have beneficial effects on nutrient cycling and conservation within forest stands and this depends on the type of understorey species (Fisher and Stone, 1969; Tappeiner and Hugo, 1973; Tappeiner and Alm, 1975; Zou *et al.*, 1995; Condron *et al.*, 1996; O'Connell and Grove, 1996; Binkley *et al.*, 2000).

2.10.1 Nitrogen supply by understorey legumes

Leguminous understorey vegetation may have a significant role in supplying N to forest ecosystems. Watt *et al.* (2003c) suggested that the presence of broom (*Cytisus scoparius* L.), a leguminous understorey, under *P. radiata* may enhance long-term growth of the tree on wet sites through N released from the death of the broom after radiata canopy closure. In a dry site he found that broom competed for soil N with radiata trees.

Binkley *et al.* (1984) studied the effects of Sitka alder (*Alnus sinuata* (Regel) Rydb.), a leguminous shrubby species, in a 23-year-old Douglas-fir stand in a gravely clay loam Typic Haplorthod, in British Columbia, Canada. They reported that when Sitka alder was present in the forest, the above-ground ecosystem biomass was 55% greater than when it was absent. The above-ground biomass of Sitka alder was 21% of the total aboveground ecosystem biomass. In the presence of Sitka alder, total aboveground biomass and stem biomass of Douglas-fir were higher than those in the absence of the Sitka alder (by 20% and 30%, respectively). The needle N concentration of the Douglas-fir stand in the presence of Sitka alder was significantly higher than that in the absence of this understorey. The total N content in the aboveground biomass and forest floor was 558 kg ha^{-1} in the presence of Sitka alder and 208 kg ha^{-1} in its absence. Of these quantities of total N, the N content in the aboveground biomass of Douglas-fir was 155 kg ha^{-1} in the presence of this understorey and 129 kg ha^{-1} in the absence of this understorey.

Klemmedson (1994) reported that the presence of New Mexican locust (*Robinia neomexicana* Gray), an N-fixing spiny shrub under ponderosa pine (*P. ponderosa* Douglas), significantly increased N concentration (0.314% for pine-locust stands and 0.173% for pine-alone stands) in the upper soil layer (0-5 cm) under the pines, as well as pine needle N concentration (1.07% for pine-locust stands vs 0.90% for pine-alone stands) in a forest on montmorillonitic Typic Agriborolls at the Coconino National Forest, Arizona, USA.

2.10.2 Nutrient storage and release by understorey vegetation

The nutrient contents in the understorey litterfall may make a significant contribution to the total nutrient pool in the forest soil. Binkley *et al.* (1984) reported that in the presence of Sitka alder under Douglas-fir for over 23 years, total litterfall dry matter weight (litter from Douglas-fir + Sitka alder) was 3.6 times higher and the nutrient contents (N, P. K, Ca and Mg) in the litterfall were 3 to 7 times higher than when Sitka alder was absent. In addition, the available N, P, Ca, and Mg concentrations in the top 10 cm soil depth were significantly increased by the presence of the Sitka alder.

Similarly, Tappeiner and Alm (1975) reported that the presence of understorey vegetation significantly increased Ca, N, K, Mg and P contents in the litterfall, compared with litterfall under pure red pine stands. Based on these results, they suggested that the understorey vegetation accumulates, stores and releases nutrients. The understorey litterfall also increased the total organic matter content in the litter layer of the forest. However, the rate of decomposition of this organic matter was faster in the presence of understorey vegetation, especially hazel and herbs (*Aster macrophyllum* L., *Pteridium aquilinum*, *Maianthenum canadense* Desf., *Diervilla lonicera* Mill., *Arctostaphylos uva-ursi* (L.) Spreng.) compared to under red pine stands without understorey vegetation. This suggests that the presence of certain understorey species in forest stands might increase the tree growth through their role in accelerating nutrient cycling and enhancing the availability of nutrients in forest ecosystems.

Maclean and Wein (1977) reported that understorey species in a 13-16-year *P. banksiana* stand had significant quantities of nutrients in the above-ground biomass. They found that the understorey species had 25% of the N and Ca, 30% of P, 40% of the Mg, and more than 65% of the K in the aboveground ecosystem.

2.11 Understorey vegetation effect on P availability to tree crops

Plants may influence the chemical and biological properties within their rhizosphere, and in this way they may enhance the soil P availability and the P uptake of neighbouring plant species. Several mechanisms have been suggested for this increased soil P availability (Binkley *et al.*, 1984; Horst *et al.*, 2001; Li *et al.*, 2003ab; Trolove *et al.*, 2003; Zhang *et al.*, 2004) and these are discussed below.

Binkley *et al.* (1984) reported that the presence of Sitka alder in Douglas-fir forest significantly increased Bray-1 P concentration (21 μg P g^{-1}) in the topsoil (0-10 cm) compared with that in the absence of this understorey (8 μg P g^{-1}). They considered this increase in Bray-1 P concentration to be related to the significant increase in P input through litterfall biomass in the presence of Sitka alder.

Recently, Sarno *et al.* (2004) reported that the presence of *Paspalum conjugatum* (introduced-understorey) or native understorey species (*Chromolaena odorata, Clibadium surinamense, Clidemia hirta, Imperata cylindrica, Melastoma affine, Mikania micrantha,* and *P. conjugatum*) in a coffee plantation in a Vertic Dystrudept at Lampung, Indonesia, increased available P compared with available P in the absence of these understorey species in both the 0-10 cm (13.3 μg P g^{-1} soil for weed-free plots, 14.9 μg P g^{-1} soil for plots with *P. conjugatum* plots, and 32.5 μg P g^{-1} soil for plots with native understorey) and the 10-20 cm soil depths (3.9 μg P g^{-1} soil, 6.6 μg P g^{-1} soil, and 10.8 μg P g^{-1} soil, respectively). In another study in Indonesia, Salam *et al.* (2001) reported that in a coffee plantation, soil phosphatase activities in bulk soils in the plots with *P. conjugatum* and with native understorey (135 and 158 μg *p*-nitrophenol g^{-1} h^{-1},

respectively) were higher than those in the plots without understorey (weed-free) (108 μg *p*-nitrophenol g^{-1} h^{-1}). In the rhizosphere soils the phosphatase activity difference between these plots, might have been even higher (Trolove *et al.*, 2003) but this was not measured in this study. Total P uptakes by the trees in plots with and without understorey species were also not reported in these studies.

There have been many reports suggesting that N-fixing plant species facilitated their neighbours by increasing soil P availability. Giardina *et al.* (1995) studied the effect of red alder (*Alnus rubra* Bong), an N-fixing understorey species, in a 21-year old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantation on soil phosphate chemistry in a deep gravely clay loam soil at Oregon, USA. They reported that the soils (0-15 cm) under red alder + Douglas-fir had significantly higher concentrations of anion resin-P_i, NaOH-P_i, and HCl-P_i (65-225% greater) than those under pure Douglas-fir. The soil phosphatase activity under red alder + Douglas-fir (29 μmol *p*-nitrophenol g^{-1} h^{-1}) was also higher than that under pure Douglas-fir (10 μmol *p*-nitrophenol g^{-1} h^{-1}). They explained the increased P_i availability (resin-P_i) under red alder + Douglas-fir as partly due to the increased soil phosphatase activity converting P_o to P_i in the soils.

Under a 63-year old mixed-conifer (Douglas-fir, western hemlock, and Sitka spruce) plantation with red alder understorey on a mesic Andic Haplumbrept at the Cascade Head Experimental Forest, Oregon, USA, Zou *et al.* (1995) reported that labile inorganic P pools (resin- and $NaHCO_3$-extractable P_i) in the soil under red alder + mixed conifers were three to fourfold higher than those under red alder or mixed conifers. They also reported that the mixed conifer stand had the highest soil pH (5.3), but the net P solubilisation rate under this stand (9 mg kg^{-1} d^{-1}) was similar to that under the red alder (12 mg kg^{-1} d^{-1}), while the red alder + mixed conifers had the lowest pH (4.8) and the highest net P solubilisation rate (51 mg kg^{-1} d^{-1}). Soil phosphatase activity under the red alder + mixed conifer stand was also higher than those in the pure mixed conifer stand and red alder. These observations led Zou *et al.* (1995) to suggest that the interaction between red alder and conifers was the cause for the increase in labile soil P pool.

Further evidence of the role of understorey vegetation in enhancing P uptake by trees was provided by Gillespie and Pope (1989). They reported that when walnut (*Juglans nigra* L.) tree seedlings interplanted with alfalfa (*Medicago sativa* L.) grown in pots containing Typic Argiaquoll soils treated with synthetic hydroxyapatite (a calcium phosphate mineral), the tree seedlings had greater P uptake compared with when the walnut seedlings were grown alone. They considered that the diffusion of solubilised phosphate rock-P to the roots of walnut at the points of root intersection with alfalfa was the mechanism for the greater P uptake by walnut seedlings. This was caused by H^+ ions diffusing from the roots of alfalfa decreasing pH, thereby, solubilising the rock phosphate.

In addition to the above studies, others have demonstrated the facilitation of P uptake in intercropping systems where legume crops were cultivated with other crop species. For example, white lupin (*Lupinus albus* L.) facilitated P uptake by wheat when they were grown in association in the field (Gardner and Boundy, 1983). In a pot experiment, Li *et al.* (2003b) showed that chickpea helped wheat to take up P from an organic P source. They suggested that chickpea hydrolysed organic P by the phosphatase released from its roots, thereby, contributing to the P uptake by wheat.

2.12 Understorey vegetation effect on P availability to *P. radiata*

To date, only limited information is available on the effect of understorey vegetation on soil P dynamics and P nutrition of *P. radiata* trees. Richardson *et al.* (1996) reported, at the end of 3 to 4 years of growing *P. radiata* with different weed species in a moderately fertile Pumice Soil in the field at Rotorua, New Zealand (Richardson *et al.*, 1993), some species of grass, herbaceous broadleaves and buddleia significantly increased P concentrations in the *P. radiata* needles (synergism), but broom, gorse, lotus and pampas had no significant effect on the needle P concentrations (Table 2.1). However, the effect of these plant species on the P concentration in other parts of the tree, total P uptake by the tree from the soil, or soil P changes due to these understorey

species were not reported in their study. The mechanism by which the plant species influenced the P nutrition of the tree was also not reported.

Table 2.1 Needle P concentration of 3-4-year-old *P. radiata* grown with different weed species in a Pumice Soil at Rotorua, New Zealand (adapted from Richardson *et al.*, 1996)

Weed type	P concentration (%)
No weeds	0.112 b*
Broom	0.119 b
Buddleia	0.140 a
Gorse	0.106 b
Grass	0.153 a
Herbaceous broadleaves	0.136 a
Lotus	0.116 b
Pampas	0.127 b

*Numbers within the same column followed by the same letters are not different at $P<0.05$

More recently, Scott (2002) conducted a pot experiment in a glasshouse to study the effects of understorey species on *P. radiata* growth, P uptake and soil P changes in four soils, namely a low P, low C soil (320 μg P g^{-1}; 2.5% C), a low P, high C soil (524 μg P g^{-1}; 5.1% C), a high P, low C soil (721 μg P g^{-1}; 2.4% C), and a high P, high C soil (768 μg P g^{-1}; 4.0% C). The understorey species tested were lucerne and ryegrass. The experimental treatments included *P. radiata* trees grown alone (3 tree seedlings in the centre one of 3 compartments in a tray), trees and lucerne grown together (3 tree seedlings + 6 lucerne plants per pot), trees and ryegrass grown together (3 tree seedlings + 6 ryegrass plants per pot), lucerne grown alone (10 plants per pot), and ryegrass grown alone (10 plants per pot). Lucerne or ryegrass grown alone or with trees were planted in individual pots containing 100 g of soil, but the trees grown alone were planted in the centre compartment of a three-compartment tray, in which the compartments (each containing 100 g of soil) were separated by 26 μm nylon mesh.

Scott's (2002) study is very relevant to the studies reported in this thesis. The experimental design used by Scott (2002), however, had many problems. Firstly, when the trees were grown alone in the centre compartment of a tray (containing 300 g soil), the tree roots, through the ectomycorrhizal hyphae, had access to nutrients and water in the additional 200 g of soil. Thus the soil weights explored by the roots of plants in the different treatments were different (Radiata vs Radiata + Lucerne or Radiata vs Raadiata + Ryegrass). Secondly, the plant densities of treatments were variable, and this confounded the treatment effects (Silvertown, 1987; Snaydon, 1991). Although in most cases the treatment effects on plant shoot yield, P uptake and soil P changes in Scott's (2002) study were not statistically significant, and also not consistent across all four soils, there was an indication on one soil that lucerne had a positive effect on tree growth and P uptake. Similarly, on some soils lucerne appeared to facilitate redistribution of P from the less labile to the more labile fraction. These are interesting findings and may help to explain the field observation by Richardson *et al.* (1996) of the beneficial effects of some understorey species on P nutrition of *P. radiata.* But the difficulties in the trial design mean that more work is required to draw firmer conclusions.

2.13 Conclusions

The review of literature reveals that the above-ground understorey biomass is a significant proportion of the total aboveground biomass in *P. radiata* forests during the first 5-10 years of growth. During this period competition for nutrients, including P, and for light and water is possible depending on tree age, site fertility, climate, understorey species and their population. It is also possible that the presence of understorey vegetation under *P. radiata* plantations may have synergistic effects on tree growth and nutrition. There are several possible mechanisms governing the enhancement of nutrient availability, including P, by understorey vegetation presence in *P. radiata* forests, such as (a) rhizosphere processes, (b) understorey legumes interaction or facilitation, (c) nutrient pumping mechanisms by deep rooted weeds, and (d) turnover of litterfall and

weed death after weed control operations prior to planting and post-planting or after canopy closure.

Most of the experiments conducted to study plant interference have not been very successful. This was partly because the designs employed failed to keep the soil weight (or volume) explored by the roots constant across all treatments. The designs also failed to separate the effects of above-ground and below-ground interference, and of the intra- and interspecific interference. In the present study, presented in Chapter 5 and 6 of this thesis, the experiments were designed to address the above points.

There has been a recent trend in New Zealand's *P. radiata* forest plantations towards wider initial tree spacing and a lower initial stocking rate of *P. radiata.* The current second and third rotation radiata pine plantations have been adopting this practice. Under low stocking rates of *P. radiata*, understorey vegetation biomass is a significant proportion of total above-ground biomass in the forest, and it also has greater diversity than that under high stocking rates. Therefore, understorey vegetation can have an important effect on P uptake by *P. radiata* trees, both before and after canopy closure. Before canopy closure, understorey vegetation can have either antagonistic or synergistic effects on P uptake by *P. radiata*, depending on the understorey species, soil moisture regime, site fertility, etc. However, after canopy closure, the understorey vegetation dies and the decay of this vegetation may release P for uptake by *P. radiata*, thus supporting *P. radiata* growth.

If the understorey vegetation in these plantations competes with *P. radiata* for soil P (antagonistic effect), higher rates of P fertiliser need to be applied to the forests or the understorey vegetation needs to be controlled by applying costly herbicides. On the other hand, if the understorey vegetation has synergistic effects on P availability to *P. radiata*, then *P. radiata* P nutrition can be sustained with lower rates of P fertiliser application. This aspect needs to be investigated by conducting P fertiliser trials on *P. radiata* trees from a young age onwards, with and without understorey vegetation, on P deficient soils. This is the focus of the research study presented in Chapter 3 and 4.

Chapter 3

Effect of P Fertilisers and Weed Control on Second-rotation *P. radiata* Growth and P Uptake - The Fate of P Fertilisers Applied to Soils

3.1 Introduction

In recent times, radiata pine (*Pinus radiata)* silvicultural regimes in New Zealand have tended to be intensive, with understorey vegetation management, wider initial tree spacing and lower initial stocking rate of *P. radiata*, and application of P fertiliser (Gadgil *et al.*, 1988; Payn *et al.*, 2000). Phosphorus fertiliser has been applied routinely to the forest plantations, where necessary, since the 1960's (Ballard and Will, 1978; Payn *et al.*, 2000). The appropriate rates of P fertilisers for first-rotation *P. radiata* have been well established (Mead and Gadgil, 1978; 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 in New Zealand have shown that in general, reactive phosphate rocks (RPR) are suitable for pasture and crops which have a long growing season and do not have short-term requirements for high levels of phosphate (Harrison and Hedley, 1987; Bolan *et al.*, 1990; Rajan *et al.*, 1994), on soils having pH<6 (in water), and in areas having a mean annual rainfall >800 mm that is well distributed throughout the year (White *et al.*, 1989). However, only a few studies have been conducted on the effects of phosphate rock on the growth of *P. radiata*, and on the concentration of inorganic-P, organic-P and plant-available P in the soils (Hunter and Graham, 1983; Hunter and

Hunter 1991; Mead, 1974). The relationships between the growth of *P. radiata* trees and soil P concentrations have also not always been reported in these studies.

However, relationships between needle P concentration of *P. radiata* and soil P concentration have been determined in some studies. Ballard (1970) reported highly significant relationships between the needle P concentration of 40-year-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) in a first-rotation forest at Riverhead, which is located 20 miles north-west of Auckland city. Meanwhile, 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 and Pumice Soils in New Zealand.

The fate of applied fertiliser P in soils can be examined by determining changes in the concentration of soil P fractions at specified periods after P application. The concentration of various soil P fractions based on their solubility in chemical extracts can be determined by using sequential P extraction methods (Chang and Jackson, 1957; Williams *et al.*, 1967, Hedley *et al.*, 1982a; Perrott *et al.*, 1989a; Tiessen and Moir, 1993). Many studies have reported on the effect of P fertiliser application on P fractions in pasture soils in New Zealand (Rowarth and Tillman, 1992; Rowarth *et al.*, 1992; Perrott and Mansell, 1989; Perrott *et al.*, 1989ab, 1992). However, only a few studies have been reported on determining the effect of P fertiliser application on P fractions in radiata pine forest soils and most of these studies were conducted under laboratory or glasshouse conditions (Chen *et al.*, 2002; 2003; Condron *et al.*, 1996). In addition, the studies in field conditions focused mainly on determining the total organic and inorganic P pools without further separating the P fractions in each of these pools (Davis, 1995; Parfitt *et al.*, 1994).

Many studies have shown that understorey vegetation can reduce *P. radiata* growth and survival (Clinton *et al.*. 1994; Nambiar and Zed, 1980; Richardson *et al.*, 1996; Squire, 1977; Watt *et al.*, 2003bc). *Pinus radiata* growth increased significantly when competitive weed species were removed in a wide range of soil types in New Zealand (Richardson *et al.*, 1993). Because of this, weed control operations using herbicide are now common in the establishment of *P. radiata* plantations in New Zealand, and this operation usually results in a considerable increase in tree growth (Richardson *et al.*, 1993, 1996).

Understorey vegetation may have an important effect on the nutrient cycle within forest stands. Tappeiner and Alm (1975) reported that understorey litterfall increased organic matter in the litter layer of the forest floor, and, thereby, increased nutrient storage in the forest floor. They considered the understorey to have compartments which accumulate, store, and release nutrients. This is supported by the work of Maclean and Wein (1977), where the understorey species in a 13-16-year *P. banksiana* stand were reported to have had 25% of the N and Ca, 30% of P, 40% of the Mg, and more than 65% of the K in the above ground ecosystem.

The presence of some understorey species may have beneficial effects on overstorey growth. For example, Gillespie and Pope (1989) reported that walnut tree seedlings had greater P uptake when they were grown with alfalfa compared with walnut seedlings grown alone. Richardson *et al.* (1996) compared needle P concentrations in 3-year-old *P. radiata* trees in the presence of several weed species on a Pumice Soil (Yellow-brown loam) at Rotorua and found that grass, herbaceous broadleaves and buddleia significantly increased P concentration in *P. radiata* needles, but broom, gorse, lotus and pampas had no effect on needle P concentrations.

Furthermore, Watt *et al.* (2003b) in a study on a mixed stand of juvenile *P. radiata* and broom (*Cytisus scoaprius* L.) on a dryland site in Canterbury, New Zealand, reported that although broom fixed 111 kg N ha^{-1} $year^{-1}$ into the above-ground parts of the broom and 1 kg N ha^{-1} $year^{-1}$ of fixed N was transferred to radiata trees, soil N uptake by the broom was 29 kg N ha^{-1} $year^{-1}$. They, therefore, suggested that broom may

reduce tree growth through competition for N with the tree. They also suggested that even in the long-term, after canopy closure, radiata trees may not benefit from the enhancement of soil N from the death of broom in dryland sites. This was explained by water stress in the dry site impairing tree N uptake. However, in wet sites after canopy closure the trees may benefit from nutrients supplied from the dead broom, especially in N-deficient sites. In this regard, Watt *et al.* (2003c) questioned the benefits of controlling broom at the establishment of radiata pine plantations beyond the point necessary for normal seedling growth and survival.

To date, no information is available on the interactive effects of soluble and less soluble P fertilisers and weed control on the growth and P uptake of radiata pines. This information is required to identify appropriate P fertiliser management practices in radiata forest plantations and to develop further the P fertiliser Decision Support System (PDSS) (Payn *et al.*, 2000), which includes the interaction of understorey vegetation on P supply rates to the trees. The PDSS is expected to help forest managers to obtain a greater knowledge on the planning of P fertiliser operations and predicting responses to P fertiliser application.

3.2 Objectives

The objectives of the study reported in this chapter are:

1. To determine the effect of application of different rates of two P fertilisers (Triple superphosphate (TSP) and Ben Guerir phosphate rock (BGPR)) and weed control, and their interactions on P fractions, in an Allophanic Soil and a Pumice Soil under 4-5-year-old second-rotation *P. radiata* plantations in the central North Island of New Zealand.
2. To determine the rate of phosphate rock dissolution in the two soils.
3. To determine the effect of the treatments on plant-available P and downward movement of P in the two soils.

The effects of the treatments on tree growth and needle P concentration will be presented in Chapter 4.

3.3 Materials and methods

3.3.1 Site description

Two experiments, one at the Kaweka forest, 70 km NW of Hastings, located at 450-600 m altitude and the other at the Kinleith forest, 10 km SE of Tokoroa, located at 740 m altitude, were installed in September 2000 (through the Sustainable Management of Forest Ecosystems (SMFE) Programme) by New Zealand Forest Research Ltd. The soils are classified as Orthic Allophanic Soil (Cryands and Udands, Soil Taxonomy) at the Kaweka forest and Orthic Pumice Soil (Vitricryands, Soil Taxonomy) at the Kinleith forest (Hewitt, 1992). Typical soil profiles at the two forests are shown in Plates 3.1 and 3.2. The soils are derived from Taupo or Tongariro volcanic ash materials. Selected properties of the soils are presented in Table 3.1.

Climate at the Kinleith forest is cool and humid (mean annual RH 82%), with a mean annual rainfall of approximately 1600 mm, and without a pronounced dry period. Mean annual temperature is 12.2°C, with a February maximum monthly mean of 17.4°C and a July minimum of 6.9°C (New Zealand Meteorological Service, 1980). Climate at the Kaweka forest is also cool and humid (mean annual RH 70%), but mean annual rainfall is approximately 1412 mm, and the area also has no pronounced dry period. Mean annual temperature is 12.6°C, with a February maximum monthly mean of 16.3°C and a July minimum of 5.5°C. During the experimental period (2001 and 2002), the total rainfall for 2001 and 2002 were 1285 and 1280 mm at the Kaweka forest and 1491 and 1702 mm at Tokoroa (the closest station to the Kinleith forest), respectively (National Institute of Water and Atmospheric Research, personal communication).

At both sites, the trees were 4-5 year old second-rotation radiata pines. They were planted in 1995-1996 at the Kaweka forest (at a stocking rate of 1000 stems ha^{-1}) and in

1997 at the Kinleith forest (at a stocking rate of 670 stems ha^{-1}). Fertiliser had not been applied to either the first-rotation or to the second-rotation trees at any time. The predominant understorey species at the Kaweka forest were bracken fern (*Pteridium esculentum*), some manuka (*Leptospermum scoparium*), and brown top (*Agrostis capillaris*), while at the Kinleith forest they were Himalayan honeysuckle (*Leycesteria formosa*), buddleia (*Buddleja davidii* Franchet), and some toetoe (*Cortaderia toetoe*) (Plates 3.3 and 3.4).

Horizon	Depth (cm)	Morphology	B.D.[1] ($g\ cm^{-3}$)	pH[2]	Bray-2 P ($\mu g\ P\ g^{-1}$)
--					
-- O1	-7 - -4	Undecomposed leaf litter (L).			
O2	-4 - 0	Brown to dark brown (10 YR 2.5/1). Partly decomposed leaf litter (F); abrupt clear boundary.			
--					
A	0 - 10	Brown (10 YR 2/2) moist, loam; moderate medium crumb structure; non- sticky, non-plastic wet, very friable moist; many medium and fine roots, few large roots; smooth boundary.	0.67	5.6	2
--					
AB	10 - 23	Brown (10 YR 3/3) moist, fine sandy loam; moderate fine to medium nutty structure; non-sticky, non-plastic wet; few pumice particles; many medium and fine roots; clear to smooth boundary.	0.70	5.6	3
--					
B1	23- 64	Brown (10 YR 4/3 or 5/2) moist, sandy loam; moderate fine to moderate nutty structure; non-sticky, non-plastic wet, very friable moist; many fine roots, few medium roots; clear to smooth boundary.	0.73	5.6	3
--					
B2	64 - 86	Brown (10 YR 4/3) moist, loamy sand; moderate to strong medium nutty, non-sticky, non-plastic wet; many coarse sand size pumice particles; many fine roots; clear to smooth boundary.	0.79	5.6	1
--					
B3	86-100/151	Brown (10 YR 4/4) moist, silt loam; strong medium nutty, non-sticky, non-plastic wet; many fine roots; clear wavy.	ND	5.6	1
-- B4	100/151+	Brown (10 YR 4/4) moist, silt to clay loam; moderate medium nutty, slightly sticky, non-plastic wet, firm moist; common rounded gravel (50%), few fine roots.	ND	ND	ND

Plate 3.1 Soil profile at the Kaweka forest (an Allophanic Soil)

1. Bulk density, 2. Soil pH (1: 2.5 water), ND – not determined, NaF test was positive for all horizons indicating the presence of significant quantities of allophane

Site description

1. Date of examination: 1 May 2002
2. Description: by Asoka Senarath and A. Arivin Rivaie (Massey University)
3. Location: Blowhard Plateau, Kaweka Forest
4. Elevation: 760 m
5. Land-form: i). physiographic position: crest of the slope
   ii). surrounding land-form: rolling to hilly
6. Slope: almost flat
7. Vegetation or land use: radiata pine forest (1st rotation)
8. Climate: mean annual rainfall 1412 mm
9. Soil parent material: volcanic tephra
10. Soil drainage: class 4 - well drained
11. Soil classification: Orthic Allophanic Soil

Horizon	Depth (cm)	Morphology	B.D.[1] ($g\ cm^{-3}$)	pH[2]	Bray-2 P ($\mu g\ P\ g^{-1}$)
--					
-- O1	-5.2 - -5	Undecomposed radiata fine litter.			
-- O2	-5 - 0	Very dark grayish brown (10 YR 3/2) moist, loam; highly porous partly decomposed organic matter.	ND	5.5	8
A	0-9/12	Dark brown (10 YR 3/3) moist, loam; moderate fine to medium nutty structure; non-sticky and non-plastic wet, very friable moist; many fine to medium roots, some dead roots; clear smooth boundary.	0.63	5.5	2
--					
Bw	9/12 - 31	Dark yellowish brown (10 YR 4/4) moist; loam; moderate medium nutty structure; non-sticky and non-plastic wet, very friable moist; few fine and medium roots; few un-decomposed pumice particles (2-3 cm long and 5 cm thick); abrupt wavy boundary.	0.73	5.4	2
--					
C	31 - 70/115	Brown (10 YR 4/4) moist; very fine sandy loam; massive moist; non-sticky and non-plastic wet, firm moist; few medium and coarse roots, iron and manganese coating along dead root channels, few pockets of manganese stains.	0.72	5.6	10
--					

1. Bulk density, 2. Soil pH (1: 2.5 water), ND – not determined

Plate 3.2 Soil profile at the Kinleith forest (a Pumice Soil)

Site description

1. Date of examination: 26 February 2004
2. Description: by Asoka Senarath and A. Arivin Rivaie (Massey University)
3. Location: Hughes Road (Block I), Kinleith Forest
4. Elevation: 383 m
5. Land-form: i). physiographic position: crest of the slope
   ii). surrounding land-form: rolling to hilly
6. Slope: gently sloping 0-1%
7. Vegetation or land use: radiata pine forest (2^{nd} rotation)
8. Climate: mean annual rainfall 1600 mm
9. Soil parent material: pumice
10. Soil drainage: class 4 - well drained
11. Soil classification: Orthic Pumice Soil

Table 3.1 Selected properties of the soils (0-10 cm depth below the litter layer) at the Kaweka (Allophanic Soil) and Kinleith (Pumice Soil) forests*

Parameter		Kaweka	Kinleith
pH	(1:2.5 H_2O)	5.7	5.1
K	($cmol_c\ kg^{-1}$)	0.29	0.94
Ca	($cmol_c\ kg^{-1}$)	2.90	9.20
Mg	($cmol_c\ kg^{-1}$)	0.58	1.36
Na	($cmol_c\ kg^{-1}$)	0.12	0.10
SO_4	($\mu g\ S\ g^{-1}$)	29.3	26.5
C	(%)	5.6	7.0
N	(%)	0.27	0.40
CEC	($cmol_c\ kg^{-1}$)	14	24
P retention	(%)	92	83
Bray-2 P	($\mu g\ g^{-1}$)	4	13
Olsen P	($\mu g\ g^{-1}$)	3	6
Resin-P_i	($\mu g\ g^{-1}$)	1	9
NaOH-P_i	($\mu g\ g^{-1}$)	39	43
NaOH-P_o	($\mu g\ g^{-1}$)	130	161
H_2SO_4-P_i	($\mu g\ g^{-1}$)	17	7
Residual-P	($\mu g\ g^{-1}$)	61	45
Total P**	($\mu g\ g^{-1}$)	248	265

* see section 3.3.5. for methods of analysis

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

Plate 3.3 Understorey species at the Kaweka forest

Plate 3.4 Understorey species at the Kinleith forest

3.3.2 Experimental design and treatments

The experiments tested the effects of four rates (0, 50, 100, and 200 kg P ha^{-1}) of P applied in two forms of P fertiliser (triple superphosphate (TSP), a soluble fertiliser and "as received" Ben Guerir phosphate rock (BGPR), a less soluble fertiliser, in combination with weed control (weed and weed-free). The water and 2% citric acid soluble P concentrations of the fertilisers and the particle size distribution of BGPR are presented in Table 3.2. The treatments were replicated four times in a split-plot design at each site. Plot sizes were 30 m x 25 m. Each P rate constituted the main plots. Each main plot was divided into two split-plots constituting the two weed control treatments. Each weed split-plot consisted of 30 trees of which 20 trees were used for measurement, while the weed-free split-plot (with 10 m buffer) consisted of 15 trees with 5 measurement trees. Because the weed-free split-plot was smaller its location within the main plots depended on which end of the main plots had the largest number of uniform trees. The layout of the trials is presented in Figures 3.1 and 3.2.

Table 3.2 Chemical characteristics of the P fertilisers used for the field trials

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

*For methods of analyses see Bolan and Hedley (1987)
**Particle size distribution: 75%<0.25 mm, 85%<0.50 mm, 90%<1.00 mm

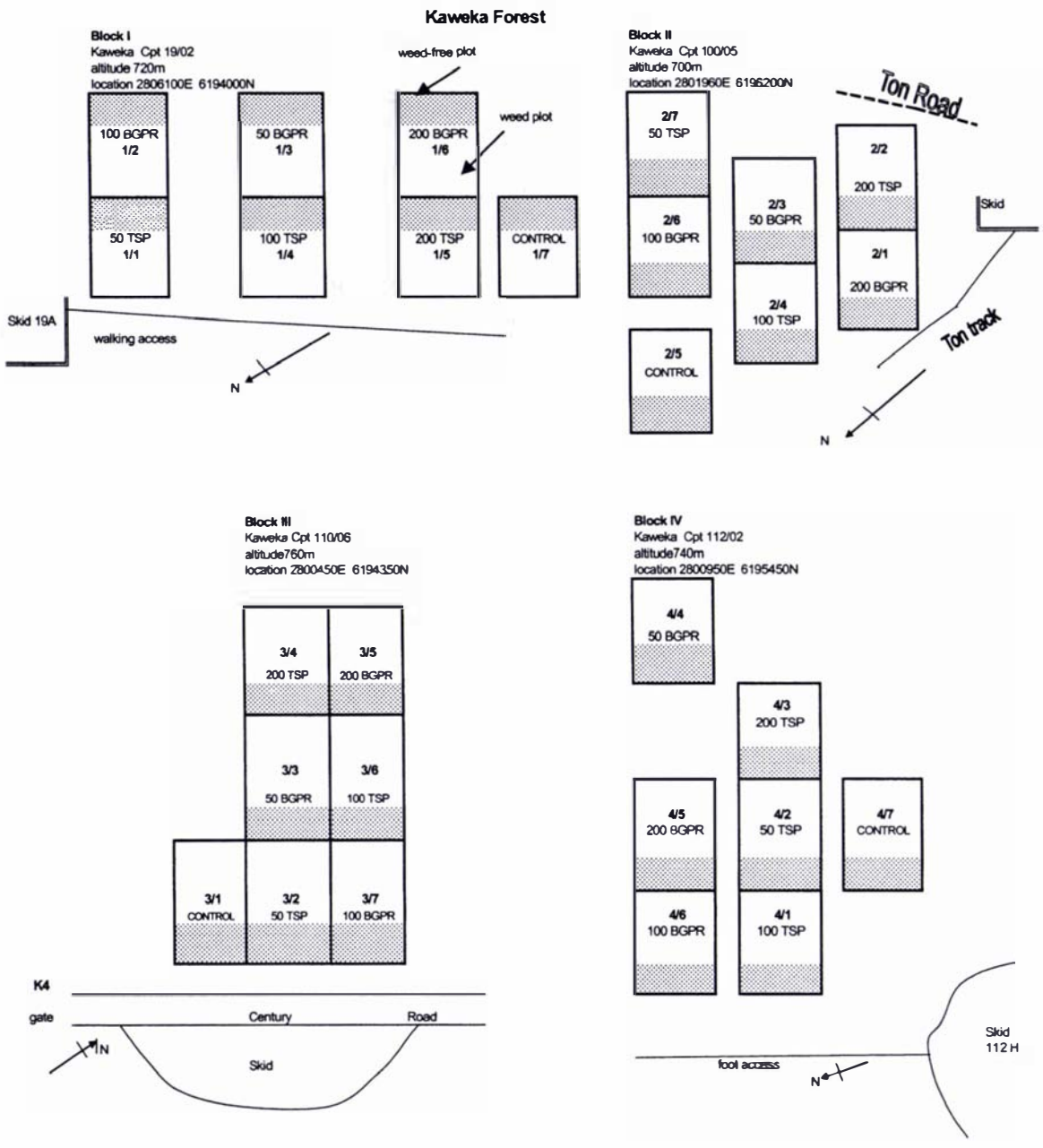

Figure 3.1 The layout of the trial at the Kaweka forest. Areas where weeds were removed are covered by dots.

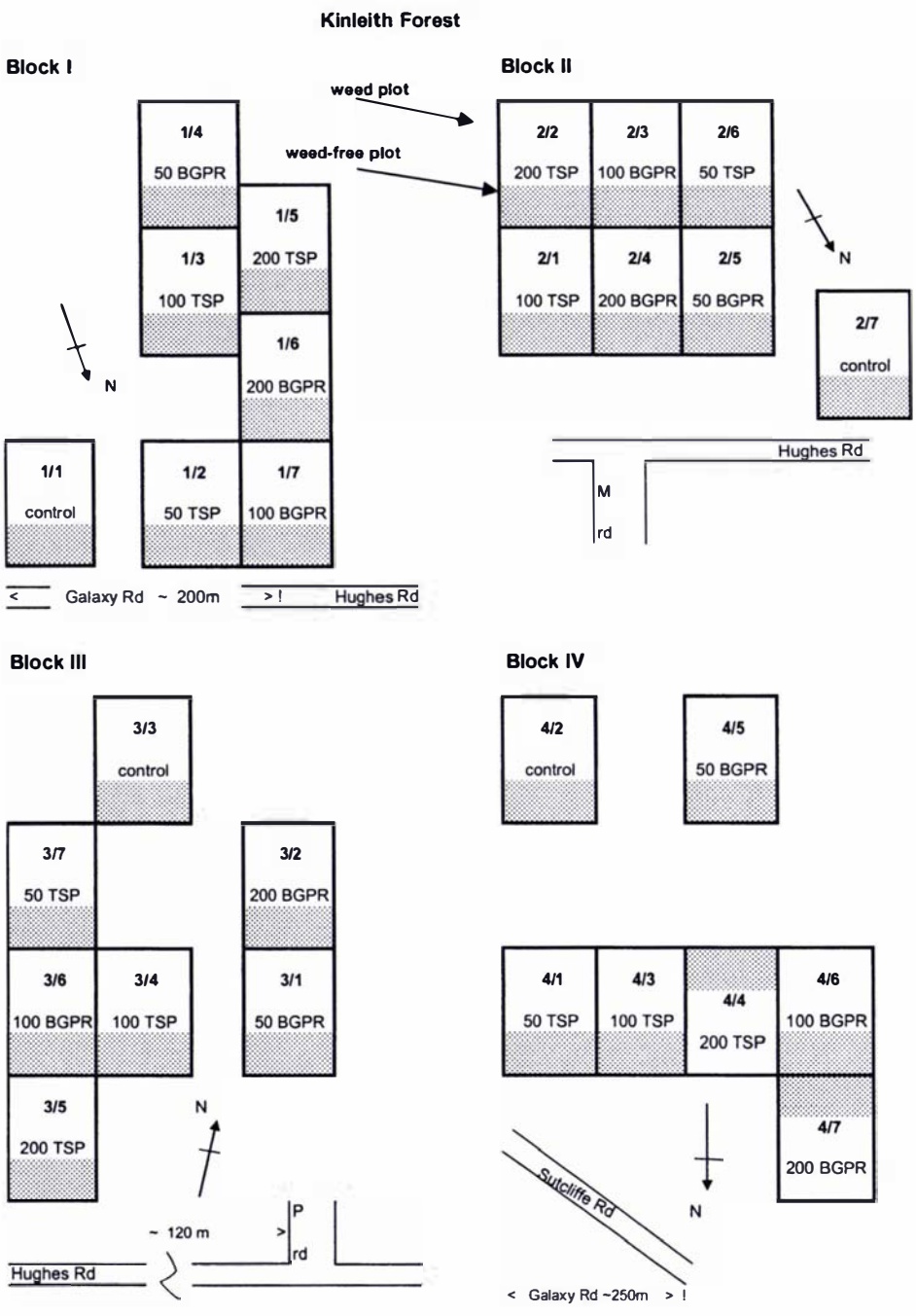

Figure 3.2 The layout of the trial at the Kinleith forest. Areas where weeds were removed are covered by dots.

At the Kaweka forest, weeds in weed-free sub-plots 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 in December 2000, May 2001, October 2001, and with a Terbuthylazine/Hexazinone mix in February 2002. At the Kinleith forest the weeds were hand-slashed during the trial establishment (9 October 2000) followed by spraying with a Gardoprim/Galant/Versatil mix in October 2001, and with a Terbuthylazine/Hexazinone mix in February 2002. The P fertilisers were applied by hand to the entire surface of the experimental plots on 4 October 2000 at the Kaweka forest and on 16 October 2000 at Kinleith forest.

3.3.3 Soil sampling

Soil samples were collected in November 2001 and December 2002 at the Kaweka forest and in December 2001 and December 2002 at Kinleith forest, (using a 2 cm-diameter soil corer. Twenty (weed-free plots) or thirty (weed plots) soil cores were taken 1.5 m from the stem of each measurement tree at soil depths of 0-10, 10-20, and 20-30 cm and the cores at each depth and treatment were combined. All soil samples were air-dried and passed through a 2 mm sieve to remove debris (obvious root and foliage) and the sieved samples were stored for chemical analyses. Soils were also collected from the 4 blocks at each site before the experiment was commenced and analysed to determine the soil P status and soil properties before starting the trials.

3.3.4 Chemical analysis

Soil cation exchange capacity and exchangeable cations

Cation exchange capacity was determined by a semi-micro leaching procedure by mixing 1 g of soil (air-dry, < 2 mm) with 2 g of acid-washed silica sand and packing into a semi micro leaching tube having a macerated filter paper plug at the bottom of the tube. The soil was leached with 50 ml of 1 M ammonium acetate (pH 7) and the

leachate collected into a 50-ml flask and made to 50 ml volume with water (Leachate 1). The leached soil was washed several times with small amounts of ethanol, allowing time to drain between each washing. A 50-ml volumetric flask was placed under each of the leaching tubes, and the soils were leached with 45 ml of 1 M NaCl. The leachate volume was made to 50 ml with water (Leachate 2). The concentrations of K, Ca, Mg, and Na in Leachate 1 were determined by atomic absorption spectrometry (AAS) and the ammonium concentration in Leachate 2 was determined using an Autoanalyser (Blackmore *et al.*, 1987). A blank determination was carried out on 2 g of acid-washed silica sand using the same procedure used for the soil.

Total organic C

The samples were heated in a stream of high purity oxygen in a Leco furnace to produce CO_2. The CO_2 is measured with an infrared detector (Leco Co., 1996) from which total organic carbon is determined..

Total organic N

Soil organic N was determined by weighing 1 g of soil (air-dry, < 0.25 mm) in a cigarette paper, and heating it with 4 ml of the digestion mixture (250 g K_2SO_4, 2.5 g selinium powder and 2.5 L H_2SO_4) in a pyrex tube in a aluminium block at 350°C for 4 hours. Afterwards the tube was cooled and the contents diluted to 50 ml with deionised water and mixed thoroughly in a vortex mixture. Nitrogen was analysed using an autoanalyser. A blank containing a cigarette paper instead of soil was run with each set of sample analyses (Bolan and Hedley, 1987).

Phosphate retention

Phosphate retention was determined by shaking a 5 g soil sample (air dry, < 2 mm) with 25 ml of a solution, made up by mixing 8.80 g KH_2PO_4, 32.8 g CH_3COONa and 23 ml glacial acetic acid, and diluting to 2 L of water (pH 4.6 ± 0.05) for 16 hours at room temperature at 50 r.p.m (Blackmore *et al.*, 1987). Two ml of aliquot was carefully removed from the supernatant solution and pipetted into a 50 ml volumetric flask. Then 12.5 ml nitric-vanadomolybdate acid reagent was added and the volume made to 50 ml with water (Blackmore *et al.*, 1987). The solution was left to stand for 30 minutes with

frequent agitation before the absorption was read on a spectrophotometer at a wave length of 420 nm. The P concentration in the solution was determined from the absorption reading and then the P retention was calculated.

Bray-2 P

Bray-2 P was determined by shaking for one minute 2.5 g of air dry soil in 25 ml of a solution containing 0.3 M NH_4F and 0.1 M HCl (Blackmore *et al.*, 1987). The suspension was filtered through a Whatman No. 41 filter paper and the P concentration in the filtrate was analysed by the colorimetric technique of Murphy and Riley (1962).

Olsen P

Olsen P was determined by shaking 1 g of air dry soil in 20 ml of 0.5 M $NaHCO_3$ (pH 8.5) for 30 minutes in an end-over-end shaker (Olsen *et al.*, 1954; Blackmore *et al.*, 1987), followed by filtration through a Whatman No. 41 filter paper. Phosphorus concentration in the filtrate was analysed by the colorimetric technique of Murphy and Riley (1962).

Soil P fractions

Soil P fractions were determined by the P fractionation procedure of Hedley *et al.* (1994). A 1 g soil sample was placed into a 50 ml polypropylene centrifuge tube and the following P fractions were sequentially separated.

(1) Resin-P_i: by shaking end-over-end for 16 hours at 25°C in 30 ml of deionised water containing a Na^+-saturated cation exchange resin membrane strip and a HCO_3^--saturated anion exchange resin membrane strip. At the end of the shaking, the strips were transferred into 50 ml centrifuge tubes using tweezers and the P retained on the resin strips was eluted by shaking end-over-end for 30 minutes with 20 ml of 0.5 M NaCl.

(2) 0.1 M NaOH-P_i: 3.3 ml of 1 M NaOH was added to the suspension from step (1) to make the final concentration of the NaOH solution in the suspension 0.1 M. The tubes with the contents were shaken for a further 16 hours. Samples were then centrifuged at

8000 rpm for 10 minutes and the supernatant filtered through a 0.45 μm Millipore filter.

(3) 0.1 M NaOH-P_o: 5 ml of the 0.1 M NaOH extractant from (2) was digested with 4 ml of concentrated H_2SO_4 (95-97%) and 1 ml of H_2O_2 (30%). The NaOH-P_o concentration was calculated by subtracting the 0.1 M NaOH-P_i concentration in (2) from the concentration of P in the digest.

(4) H_2SO_4-P_i: 30 ml of 0.5 M H_2SO_4 was added to the soil residue from step (3) and the contents were shaken for 16 hours, centrifuged and filtered.

(5) Residual-P: The soil residue from step (4) was digested with 8 ml of concentrated H_2SO_4 (95-97%) at 350°C for 3 h, cooled, 0.5 ml H_2SO_4 (95-97%) added and reheated until the residue was white. The digests were then made up to 50 ml with deionised water and filtered through a 0.45 μm Millipore filter. To avoid the precipitation of Fe-hydroxide and to minimise the use of NaOH in neutralisation, only a 5 ml aliquot was transferred into a 50 ml flask and neutralized with a 5 M of NaOH using a *p*-nitrophenol indicator.

The P concentrations in all the above extracts and digests were measured by the colorimetric technique of Murphy and Riley (1962).

The P fractions delineated by this procedure approximately correspond to the following soil P pools (Hedley *et al.*, 1982a):

P fraction	Chemical nature of P
Resin-P_i	Inorganic P that is freely available to the plant
0.1 M NaOH-P_i	Inorganic P adsorbed to Fe and Al hydrous oxide and allophane
0.1 M NaOH-P_o	Organic P adsorbed to 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

Plant uptake of P_i from soil has been shown to be mainly from the resin-P_i fraction, but 0.1 M NaOH-P_i fraction can also supply P to plants in the long-term (Hedley *et al.*, 1982a; Trolove *et al.*, 2003). These two fractions can be grouped together and called labile-P_i.

3.3.5 BGPR dissolution in laboratory incubated soils

The objective of this study was to measure whether or not there was any difference in the rate of dissolution of BGPR fertiliser between the Allophanic and the Pumice Soils. The soils were mixed with this fertiliser and incubated for 66 days. The results of this study were expected to explain the dissolution characteristics of BGPR in the soils at the field trials.

The soils used were collected from the 0-10 cm soil depth in unfertilised areas at the Kaweka and Kinleith forests. The soils were air dried and ground to pass through a 2 mm sieve. Sub-samples of soil (100 g) were mixed thoroughly with BGPR (particle size of 75-150 μm) at the rates of 50, 100, and 200 μg P g^{-1} soil (equivalent to 50, 100, and 200 kg P ha^{-1}, respectively; B.D used = 1 g cm^{-3}) in polythene bags. Each treatment was duplicated. The soils were kept at 80% field capacity moisture content by

weighing the bag + soil once a week and adding deionised water to bring the weight of soil to the required moisture content. The soil/fertiliser mixtures were stored in a dark room at 16 ± 2°C. The trial had a control treatment consisting of soils without P addition. After 66 days of incubation, the soils were dried and sequentially extracted according to the procedure of Hedley *et al.* (1982a). The increase in P in the 0.5 M H_2SO_4 extract of fertilised soils, compared to unfertilised (control) soils after the removal of P dissolved from PR by resin and NaOH extraction, was assumed to be due to the extraction of residual PR (undissolved PR).

The percent dissolution of the added fertiliser in each soil sample was calculated using the following equation:

$$\% \text{ dissolution} = 100 \left[1 - \frac{0.5\ \text{M}\ H_2SO_4 \text{ extractable P } [(\text{soil + P fertiliser}) - (\text{soil alone})]}{\text{fertiliser P added}}\right]$$

Tambunan *et al.* (1992) reported that PR dissolution determined by using NaCl/TEA (pH 7) instead of resin in the 1st extraction step of the sequential P extraction method gave an accurate and lower measure of PR dissolution compared to when resin was used in the 1st extraction step. This is because in Tambunan *et al's* (1992) scheme, a buffered neutral pH medium is used where the PR does not dissolve during extraction, unlike in the resin method where the soils are not buffered and, therefore, PR may dissolve in the acidic soil condition during resin extraction. However, Liu *et al.* (2004a) reported that the dissolution values obtained for Sechura phosphate rock (SPR) in the Kaweka soil using the two procedures were approximately the same. As the resin method is used in this study to determine plant-available P, BGPR dissolution was also determined by the P fractionation procedure using resin as the 1st step of extraction.

3.3.6 BGPR dissolution in field soils

The dissolution of BGPR in the field soils was determined on the 0-10 cm depth soil samples collected in 2002 according to the method described in the preceding section (section 3.3.5).

3.3.7 Statistical analysis

Analysis of variance (ANOVA) for a split-plot design was performed using SAS (SAS Institute, 2001). The least significant difference (LSD) test at $P<0.05$, unless otherwise stated, was used to separate the means when analysis of variance (ANOVA) results indicated that there were significant treatment effects (Steel *et al.*, 1997). For the Kaweka forest, resin-P_i data were square root transformed and NaOH-P_i and H_2SO_4-P_i data were $\log_e$ transformed, while for the Kinleith forest resin-P_i and H_2SO_4-P_i data were $\log_e$ transformed and NaOH-P_i data was square root transformed. The data were square root transformed when the spreads (or standard deviation) were proportional to the square root of the mean; and the data were $\log_e$ transformed when the spreads (or standard deviation) were proportional to the treatment mean (Anon, 2000).

3.4 Results and discussion

3.4.1 Soil P fractions

3.4.1.1 Resin-P_i

At the Kaweka forest, in 2001 and 2002, application of TSP and BGPR significantly ($p<0.0001$ and $p=0.0019$, respectively) increased resin-P_i concentrations. At the Kinleith forest, however, the application of P fertilisers significantly ($p<0.0001$) increased resin-P_i concentrations only in 2001 (Figure 3.3).

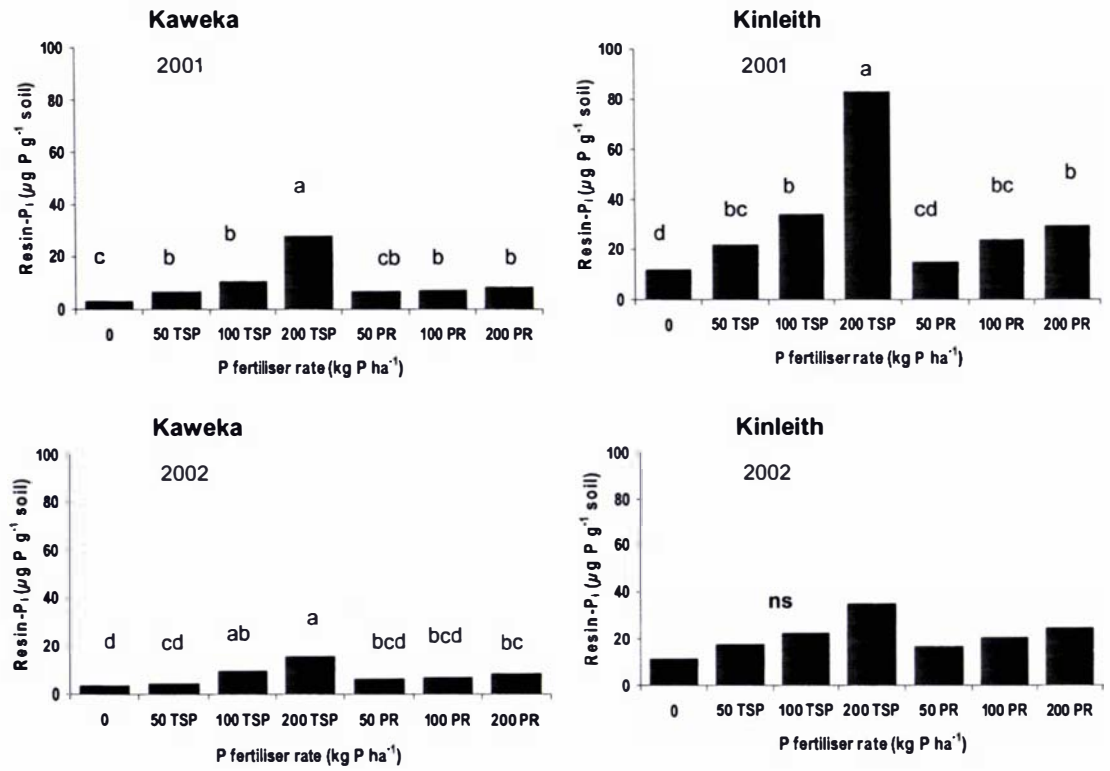

Figure 3.3 Effect of P fertiliser rates on resin-P_i concentrations after 1 and 2 years of P application (2001 and 2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
Statistical analysis was carried out on $\sqrt{Y}$ transformed data for the Kaweka forest for both years. For the Kinleith forest, a statistical analysis was carried out on $\log_e$ transformed data for 2001
*Bars having the same letters at the top are not different at $P<0.05$

The magnitude of the increase in resin-P_i concentration due to the addition of TSP was higher than due to BGPR addition at both forests. This is because of the higher solubility (water and citric acid solubility) of TSP than BGPR (Table 3.2). At both forests, during 2001 and 2002, the addition of BGPR at rates of 100 and 200 kg P ha^{-1} gave resin-P_i concentrations approximately equal to that of the TSP addition at the rates of 50 and 100 kg P ha^{-1}.

The reason for the increased resin-P_i concentration even when the relatively insoluble BGPR was applied is that at both forest sites the soils had pH values (5.7 at Kaweka and 5.1 at Kinleith) lower than the upper pH limit of 6.0 for PR dissolution (Mackay *et*

al., 1986; Bolan and Hedley, 1989; White *et al.*, 1989). The rainfall in 2001 and 2002 at the Kaweka and the Kinleith forests (1285 and 1280 mm at Kaweka forest and 1491 and 1702 mm at Kinleith forest, respectively) (National Institute of Water and Atmospheric Research, personal communication)) was also higher than the minimum annual rainfall of 800 mm required for PR dissolution (White *et al.*, 1989). In 2002 the resin-P_i concentrations in the TSP-treated soils, especially at 200 kg P ha^{-1}, were lower than those in 2001 at both forests. This is probably because with time the amount of P fixation in soil may have increased, resulting in increased conversion of resin-P_i to NaOH-P_i. But for BGPR there was no change in resin-P_i concentrations between 2001 and 2002. This is because BGPR dissolution would have continued over time counteracting the increased amount of P fixation and plant P uptake.

The magnitude of increase in resin-P_i concentration with increased P fertiliser rates at the Kaweka forest is lower than that at the Kinleith forest. This is probably due to the Allophanic Soil at the Kaweka forest having a higher P fixing capacity than the Pumice Soil at the Kinleith forest. Hence proportionately more of the fertiliser-P added had been converted into less available soil P fractions at the Kaweka forest (Clark and McBride, 1984; Parfitt, 1989).

The weed removal at the Kaweka forest in 2002 significantly ($p<0.0156$) increased the resin-P_i concentration (Figure 3.4). In contrast, at the Kinleith forest the presence of weeds resulted in a significantly higher resin-P_i concentration ($p<0.0471$) than in the absence of weeds. In 2001 the weed control effects at both forests were similar to those in 2002 but were not statistically significant. The higher resin-P_i concentration in weed-free plots than in weed plots at Kaweka forest suggested that there was competition for soil plant-available P between radiata trees and weeds in this highly P-deficient soil (Bray-2 P 4 $\mu g\ g^{-1}$). In the Kinleith soil there would have been no or less competition for P between radiata pines and weeds as the natural soil plant-available P was already high (Bray-2 P 13 $\mu g\ g^{-1}$). The beneficial effects of weeds on resin-P_i concentrations at the Kinleith forest may have been due to the presence of predominately Himalayan-honey suckle, buddleia, and some toetoe at this forest. Himalayan-honey suckle and buddleia are shrubs that are deciduous and have a more intensive and deeper root

system than the understorey species (bracken fern and manuka) at the Kaweka forest (Roy *et al.*, 1998). Toetoe also has an intensive, deep rooting system. The root system of the weed species in the Kinleith forest may have had a significant role in enhancing plant-available P (resin-P_i) of topsoil through P uptake from deeper horizons and return to the soil surface in the form of litter (pumping mechanism) (Davis and Lang, 1991). Other root processes of the weeds such as acidification and organic anion excretion may have also increased resin-P_i concentration by mobilisation of some insoluble P in the soils (Marschner *et al.*, 1986; Tarafdar and Jungk, 1987; Gahoonia and Nielsen, 1992; Hinsinger and Gilkes, 1997; Jones, 1998).

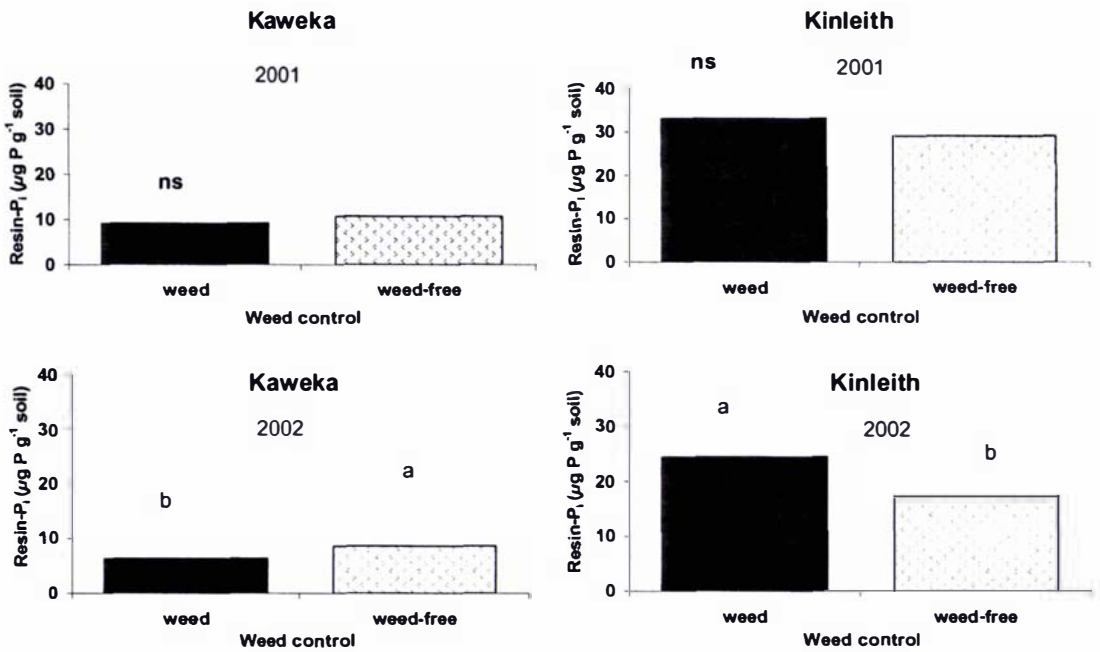

Figure 3.4 Effect of weed control on resin-P_i concentration after 1 and 2 years of weed control treatment (2001 and 2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

Statistical analysis was carried out on $\sqrt{Y}$ transformed data for Kaweka forest and on $\log_e$ transformed data for the Kinleith forest for 2 years after weed control treatment

*Bars having different letters at the top are significantly different at $P<0.05$

Though the main effect of weed control (Figure 3.4) was not significant in 2001, there was a significant interaction ($p<0.0396$) between P fertiliser rates and weed control on resin-P_i concentrations in the Kinleith soil in 2001 (Table 3.3; Figure 3.5). At low P rates (0, 50 and 100 kg P-TSP and P-BGPR ha^{-1}) there was no significant difference in

resin-P_i concentrations between weed and weed-free plots at the Kinleith forest. Whereas, at the rate of application of 200 kg P-BGPR ha^{-1}, the presence of weeds significantly increased resin-P_i concentrations compared to no-weed plots, as observed for the main effects of weeds in 2002 at this forest. The magnitude of the increase was however small and difficult to explain. A possible reason for the higher resin-P_i concentrations in weed plots at the higher P rates at the Kinleith forest is that at the higher rates of P application weeds enriched the topsoil with P removed from the subsoil through the pumping mechanism discussed in the preceding paragraph. At high P rates, P from fertilisers was observed to have moved to deeper soil layers at the Kinleith forest (see section 3.4.5)

Table 3.3 Effect of interaction between P fertiliser rates and weed control on resin-P_i concentrations after 1 year of treatment application (2001) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

P fertiliser rate (kg P ha^{-1})	Kaweka[1]		Kinleith[2]	
	Weed	Weed-free	Weed	Weed-free
	..... μg P g^{-1} soil			
0	3.2	2.7	8.9 a E[3]	14.4 a B
50 TSP	6.0	7.1	14.7 a DE	28.5 a B
100 TSP	6.0	15.0	41.4 a B	26.3 a B
200 TSP	27.1	28.5	88.7 a A	78.1 a A
50 BGPR	6.6	6.7	15.4 a DE	14.0 a B
100 BGPR	6.7	7.5	23.3 a BCD	23.9 a B
200 BGPR	8.8	7.7	39.7 a BC	18.6 b B

[1]ns (not significant)
[2]Statistical analysis was carried out on $\log_e$ transformed data
[3]Numbers within the same column followed by the same capital letters (P rate) or within the same row followed by the same lower case letters (weed control) are not significantly different at $P<0.05$

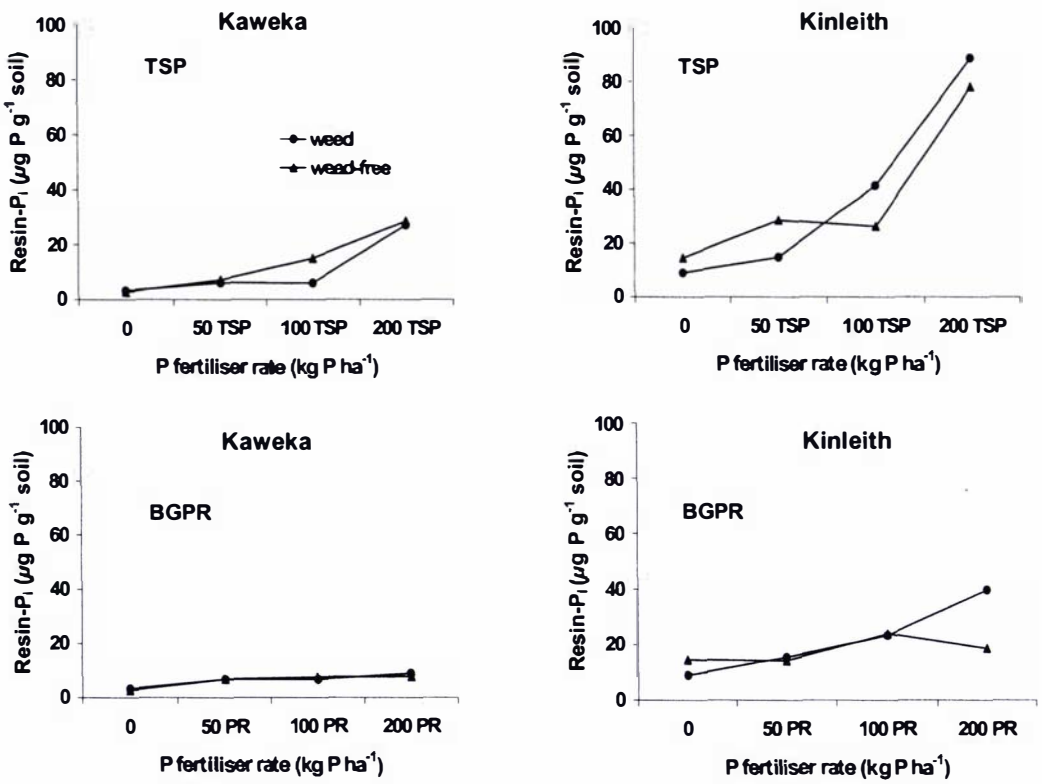

Figure 3.5 Effect of interaction between P fertiliser rates and weed control on resin-P_i concentrations after 1 year of treatment application (2001) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

3.4.1.2 NaOH-P_i

The effect of P fertiliser addition on NaOH-P_i concentrations at both the Kaweka and Kinleith forests in 2002 was significant ($p<0.0001$ and $p=0.0003$, respectively) (soil samples not analysed for NaOH-P_i in 2001). But neither weed control nor the interaction of P fertilisers and weed control on NaOH-P_i concentrations were significant at either site.

Unlike resin-P_i concentrations, NaOH-P_i concentrations, which is a measure of P adsorbed to Fe and Al oxides and allophane (Hedley *et al.*, 1982a), was higher in the Kaweka soil compared to the Kinleith soil, for the same rate of P application (Figure

3.6). This is probably because of the higher P fixation in the Allophanic Soil at the Kaweka forest compared to the Pumice Soil at Kinleith forest (Table 3.1) (Clark and McBride, 1984; Parfitt, 1989).

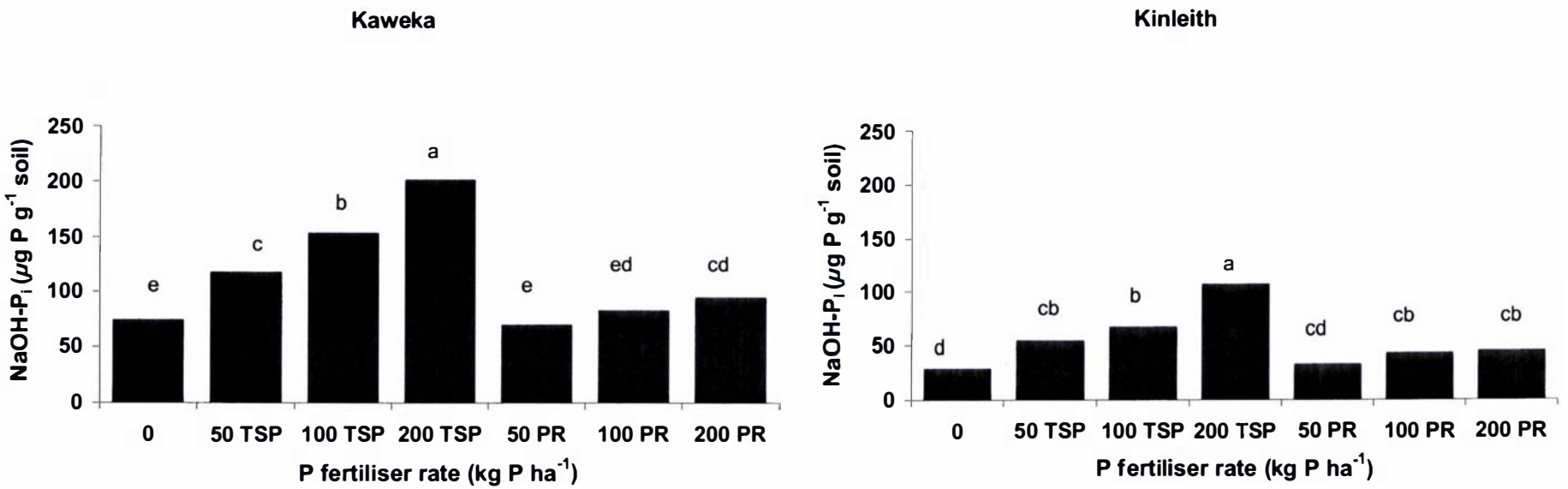

Figure 3.6 Effect of P fertiliser rates on NaOH-P_i concentrations after 2 years of P application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

Statistical analysis was carried out on $\log_e$ transformed data for both the Kaweka and Kinleith forests

*Bars having the same letters at the top are not different at $P<0.05$

The NaOH-P_i concentrations significantly increased with increase in the application rates of TSP and BGPR at both sites, but the rate of increase was higher for the TSP treatment than for the BGPR treatment. The higher rate of increase for the TSP treatment is probably due to the higher water solubility of TSP compared to BGPR (Table 3.2). When fertiliser P became soluble it might have quickly mobilized and then transformed mainly into the NaOH-P_i pool in these high P fixing soils. Zoysa *et al.* (2001) also reported that the rate of NaOH-P_i concentration increase in a high P fixing Ultisol was higher when the soils were treated with TSP compared to when the soils were treated with a PR.

3.4.1.3 NaOH-P_o

Neither P fertiliser, weed control nor their interaction had a significant effect on the NaOH-P_o concentration at the Kaweka and Kinleith forests (Figure 3.7).

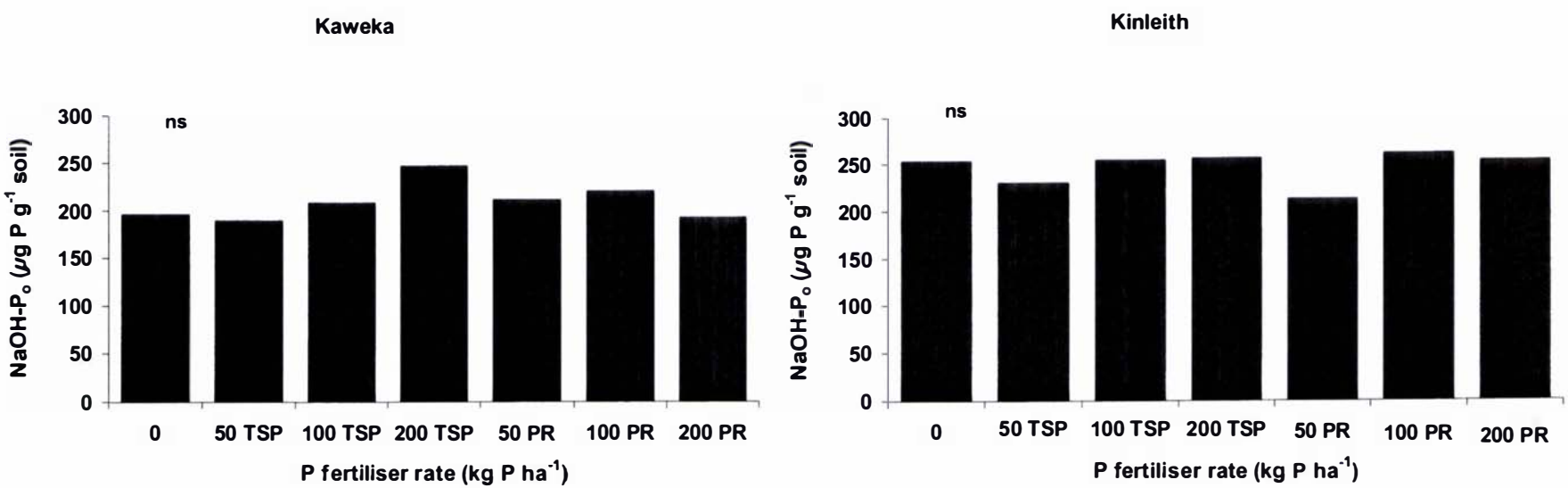

Figure 3.7 Effect of P fertiliser rates on NaOH-P_o concentrations after 2 years of P application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

3.4.1.4 H_2SO_4-P_i

The application of P fertiliser had significant effects on H_2SO_4-P_i concentrations in the soils at both forests ($p<0.0001$ and $p<0.0001$, respectively). But the effects of weed control and interaction of the P fertiliser rate and weed control on H_2SO_4-P_i concentrations were not significant.

The H_2SO_4-P_i concentrations were higher for the BGPR treatment than for the TSP treatment for all rates of P application at both trial sites (Figure 3.8). All rates of BGPR application significantly increased the H_2SO_4-P_i concentration in both the soils. This is due to the high concentration of undissolved PR (P associated with Ca) remaining in the soils, which was extracted by H_2SO_4. In comparison, the addition of TSP significantly, but only slightly, increased the H_2SO_4-P_i concentrations only at 100 and 200 kg P ha^{-1} in the Kaweka soil and at 200 kg P ha^{-1} in the Kinleith soil. Trolove *et al.* (1996) also reported that the application of North Carolina Phosphate Rock (NCPR) to a yellow-brown/yellow-grey earth intergrade (Typic Dystrocrept) in a glasshouse trial increased the H_2SO_4-P_i concentrations, while application of monocalcium phosphate which is the main P component of TSP did not increase the concentration of the H_2SO_4-P_i fraction.

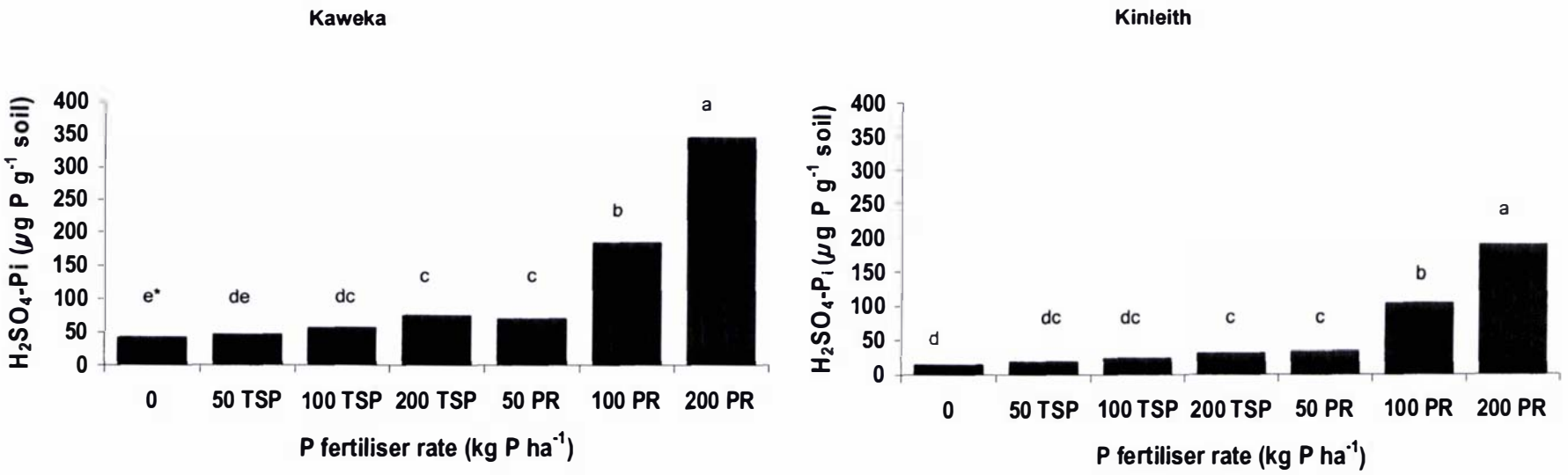

Figure 3.8 Effect of P fertiliser rates on H_2SO_4-P_i concentrations after 2 years of P application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

Statistical analysis was carried out on $\log_e$ transformed data for both the Kaweka and Kinleith forests

*Bars having the same letters at the top are not different at $P<0.05$

While the increase in H_2SO_4-P_i concentrations resulting from the increase in BGPR rates of application is due to an increase in concentration of undissolved PR, the increase in H_2SO_4-P_i with an increase in TSP rates is due to the increase in concentrations of dicalcium phosphate resulting from the conversion of MCP in TSP to dicalcium phosphate (Lehr *et al.*, 1959; Hedley *et al.*, 1994).

In general, the magnitude of the increase in H_2SO_4-P_i concentrations per unit weight of BGPR addition at the Kaweka forest was greater than that at the Kinleith forest. This may be due to the higher rate of dissolution of BGPR in the Kinleith soil than in the Kaweka soil, as the former was more acidic than the latter (pH 5.1 and pH 5.7, respectively, Table 3.1). The supply of H^+ is a driving force for the dissolution of PR, along with the removal of the dissolution reaction products Ca^{2+}, $H_2PO_4^-$ and F^- from the site of dissolution (Khasawneh and Doll, 1978). Increases in PR dissolution in allophanic soils in New Zealand, from 29.3% to 83.5%, 18.2% to 78.9%, and 12.5% to 60.3% were reported for North Carolina phosphate rock, Jordan phosphate rock and Nauru phosphate rock, respectively, when the soil pH decreased from 6.5 to 3.9 (Bolan and Hedley, 1990).

Rainfall at the Kinleith forest during the trial period was higher than at the Kaweka forest (annual rainfall for 2001 at Kinleith was 1491 mm and at Kaweka was 1285 mm; for 2002 they were 1702 and 1280 mm, respectively). It is possible that this would have resulted in a higher soil moisture regime at the Kinleith forest to help further the dissolution of BGPR. But the Kaweka soil had lower exchangeable Ca and resin-P_i concentrations and higher P fixing capacity compared to the Kinleith soil, therefore, based on these properties PR dissolution would have been expected to be higher at Kaweka soil (Mackay and Syers, 1986; Smyth and Sanchez, 1982). The fact that the observed dissolution was lower in the Kaweka soil indicates that the effect of the higher acidity and moisture content in the Kinleith soil overrides the influences of P fixing capacity, P concentration and exchangeable Ca in the soils in promoting a higher rate of BGPR dissolution in the Kinleith soil.

An attempt was made to determine the rate of BGPR dissolution in the field using the H_2SO_4-P_i data (Zoysa *et al.*, 1997), but the results showed extremely high variability and, therefore, no meaningful information on BGPR dissolution in the field soils was derived. This high variability in BGPR dissolution is probably due to high field variability and the very small percentage of BGPR dissolution. The residual BGPR contents in the soils in some plots, especially those treated with high P rates (100 and 200 kg P ha^{-1}), were nearly equal to the amounts of BGPR added or sometimes even more than the amounts of BGPR added, resulting, sometimes, in negative values for the BGPR dissolution (data not shown). The low BGPR dissolution is probably due to the low reactivity of the BGPR (2% citric acid soluble P was 28% of total P, Table 3.2).

Tambunan (1992) reported a higher percentage dissolution for North Carolina phosphate rock (80%<250 μm, 20%<150 μm) when it was applied at the rate of 80 kg P ha^{-1} to an Indonesia Entisol with soil pH (water) of 5.3. The percentage dissolution of NCPR after two years of application was 61%. The higher percent dissolution of NCPR is probably due to its higher reactivity (2% citric acid soluble P was 42% of total P).

Unlike in the field study where as-received BGPR was applied (75%<0.25 mm, 85%<0.50 mm, 90%<1.00 mm), in the laboratory incubation study, where finely ground BGPR (particle size of 75-150 μm) was used, the variability between replicates were very low and a high percentage of BGPR dissolution was obtained (Table 3.4). The laboratory study results showed that after 66 days of incubation of BGPR with soils at room temperature (16 ± 2°C and at 80% field capacity moisture content), 62-70% of BGPR dissolved in the Kaweka soil (Allophanic Soil) compared to 68-76% dissolution in the Kinleith soil (Pumice Soil). The higher percentage of BGPR dissolution in the Kinleith soil than in the Kaweka soil is consistent with the dissolution rates inferred from the H_2SO_4-P_i data for the field trial soils (Figure 3.8). As in the field study, in the laboratory incubation study the Kinleith soil had a lower pH (pH 4.8) than the Kaweka soil (pH 5.6) and, therefore, pH seems to be controlling BGPR dissolution.

Table 3.4 Percent dissolution of BGPR after 66 days of incubation in an Allophanic Soil and a Pumice Soil in a laboratory

P added (μg P g^{-1})	P added (kg P ha^{-1})*	Kaweka forest (%)	Kinleith forest (%)
50	50	70.3 ± 0.6	76.0 ± 1.9
100	100	67.8 ± 0.1	74.5 ± 0.5
200	200	62.1 ± 0.8	68.0 ± 0.2

*Equivalent rate in the field calculated using a bulk density of 1 g cm^{-3} and a soil depth of 0-10 cm

3.4.1.5 Residual-P

As with the NaOH-P_o concentrations, the residual-P concentrations in the soils at both forests were not influenced by the application of P fertiliser (Figure 3.9) and weed control. There was also no interaction of P fertiliser and weed control on residual-P concentrations at both sites.

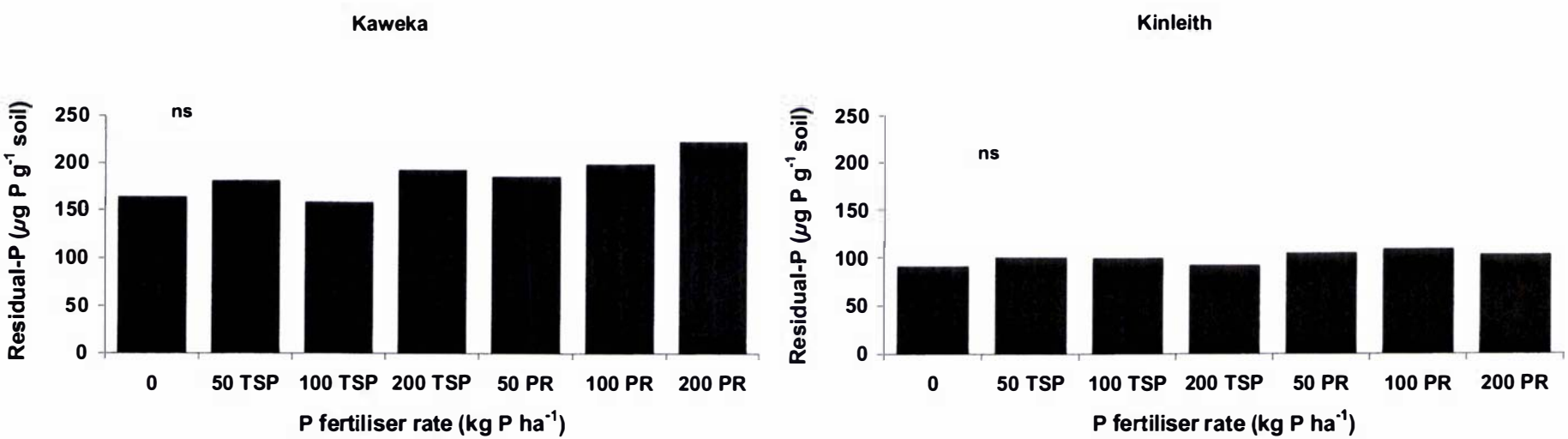

Figure 3.9 Effect of P fertiliser rates on residual-P concentrations after 2 years of P application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

3.4.2 Comparison of the fertiliser P contribution to the different soil P fractions

The data on the concentrations of the various soil P fractions two years after application of P fertiliser showed that for the TSP treated soils and for the natural soil (no P added) the P concentration in the different P fractions, in general, decreased in the order of $NaOH\text{-}P_o$ > residual-P > $NaOH\text{-}P_i$ > $H_2SO_4\text{-}P_i$ > $resin\text{-}P_i$ at both sites (averaged over weed and weed-free treatment) (Figure 3.10). For the addition of BGPR, the trend was similar to that of TSP but at the rates of 100 and 200 kg P ha^{-1} the concentrations of $H_2SO_4\text{-}P_i$ were higher than the concentrations of $NaOH\text{-}P_i$ at both sites. Furthermore, at the BGPR addition rate of 200 kg P ha^{-1} at the Kaweka forest, the concentration for the $H_2SO_4\text{-}P_i$ fraction was the highest.

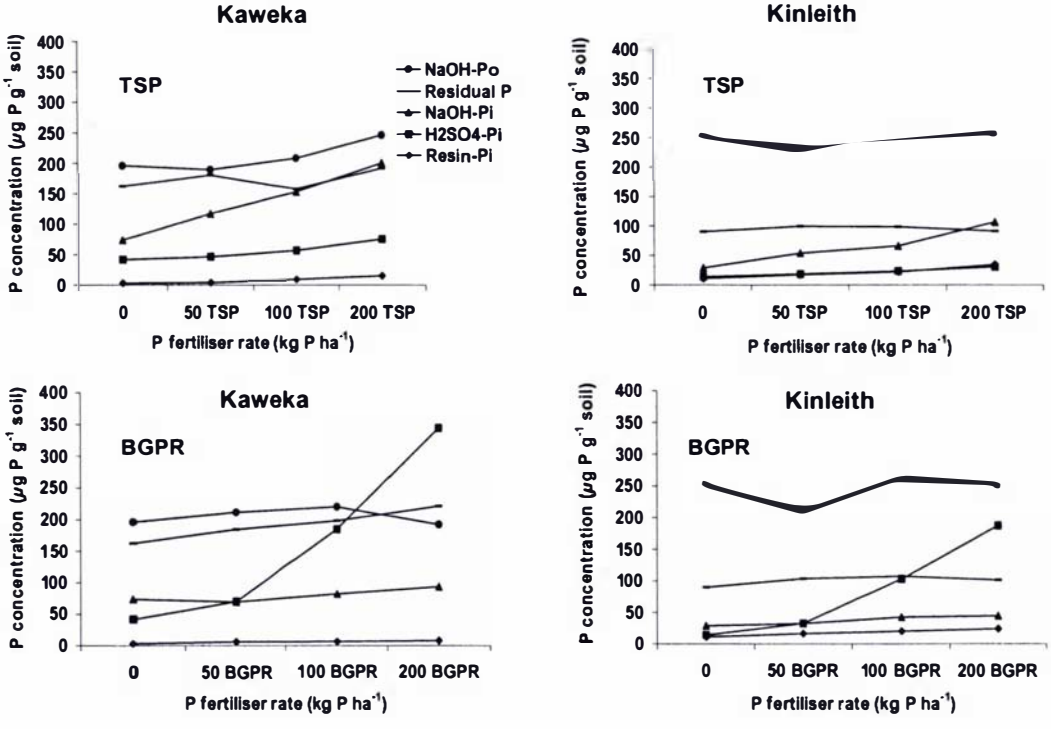

Figure 3.10 Comparison of the changes in P concentrations in different soil P fractions with increase in TSP and BGPR rates after 2 years of P application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

The pattern of change in P concentration in the different P fractions due to the additions of TSP was different from that due to the additions of BGPR. When increased rates of TSP were applied, the NaOH-P_i fraction (averaged over weed and weed-free treatments) increased at a faster rate than the other P fractions and the rate of increase was more marked at the Kaweka forest than at the Kinleith forest (Figure 3.10). This suggested that the proportion of TSP applied to the soil that was adsorbed to allophane and Fe+Al oxides was more than that converted to any of the other P fractions. The higher rate of increase of NaOH-P_i concentrations at the Kaweka forest than at the Kinleith forest is due to the higher P fixation capacity of the Kaweka soil compared to that of the Kinleith soil (Table 3.1).

Meanwhile, when increased rates of BGPR were added, the H_2SO_4-P_i fraction (averaged over weed and weed-free treatments) increased at a faster rate compared with the other P fractions and the rate of increase was also more marked at the Kaweka forest than at the Kinleith forest (Figure 3.10). The reasons for this have already been discussed previously (see section 3.4.1.4).

At both forests, increased rates of BGPR and TSP had no effect on the concentrations of NaOH-P_o and residual-P. Also, at the Kinleith forest, increasing the P fertiliser rate had no effect on the concentrations of resin-P_i. The possible reasons for these trends have also been already explained previously (section 3.4.1.1).

3.4.3 Plant-available soil P

3.4.3.1 Bray-2 P

Bray-2 P is the common soil test used for determining P availability in *P. radiata* plantation soils in New Zealand (Adams and Walker, 1973; Ballard, 1970, 1974; Davis, 2001; Giddens *et al.*, 1997; Hunter and Hunter; 1991). At the Kaweka forest, the soils that received no P fertiliser had a Bray-2 P value of 6 $\mu g\ P\ g^{-1}$, which is far below the critical P concentration of 12 $\mu g\ P\ g^{-1}$ established for the maximum yield of 1 to 3-year-

old *P. radiata* (Ballard, 1974), while at the Kinleith forest the soils had a Bray-2 P value of 15 μg P g^{-1} which is higher than the critical soil P concentrations (Figure 3.11).

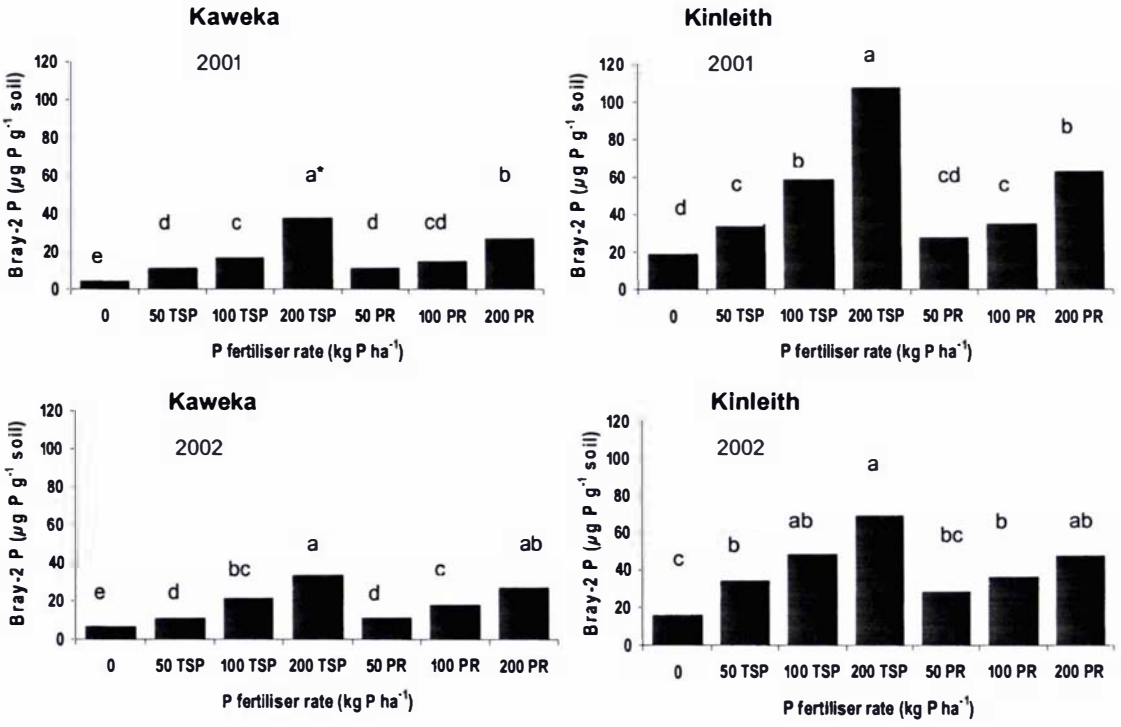

Figure 3.11 Effect of P fertiliser rates on Bray-2 P after 1 and 2 years of P application (2001 and 2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
Statistical analysis was carried out on $\sqrt{Y}$ transformed data for the Kaweka forest for 1 year after P application and on $\log_e$ transformed data for the Kaweka forest for 2 years and for the Kinleith forest for 1 and 2 years after P application
*Bars having different letters at the top are significantly different at $P<0.05$

The main effect of P fertiliser rates on Bray-2 P concentrations in the soils at both forests in 2001 and 2002 was highly significant ($p<0.0001$ and $p<0.0001$, respectively at the Kaweka forest; $p<0.0001$ and $p=0.0078$, respectively at the Kinleith forest). There was also a significant effect for weed control on Bray-2 P concentrations at the Kinleith forest in both 2001 and 2002 ($p=0.0032$ and $p=0.0411$, respectively), but not

at the Kaweka forest. There was no interaction between P fertiliser and weed control on Bray-2 P concentrations.

Increased rates of both forms of P fertilisers increased Bray-2 P concentrations in the soils at both sites in both years (2001 and 2002). These results are similar to those obtained for the effect of P fertilisers on resin-P_i concentrations (Figure 3.3), except the P fertiliser rates had no significant effect on resin-P_i concentrations at the Kinleith forest in 2002. The Bray-2 P results in this study are consistent with some of the other studies conducted in New Zealand on *P. radiata*. Ballard (1972) reported that 18 years after application of 2.5 tonnes of superphosphate ha^{-1} (225 kg P ha^{-1}) to a 20-24-year old radiata plantation on a Parau clay soil at Riverhead forest, approximately 15 miles north-west of Auckland, the Bray-2 P concentration (soil depth 0-10 cm) in the treated plots (5.4 μg P g^{-1}) was significantly greater than that in the untreated plots (2.3 μg P g^{-1}). In another trial, Hunter and Hunter (1991) reported that 7 years after the application of superphosphate or phosphate rock to three soils of different P retention capacities (P retention of 93%, 48%, and 0%), there were marked increases in the Bray P concentration in all the three soils.

In general, the magnitude of the increase in Bray-2 P concentration with the addition of P fertilisers at the Kinleith forest was higher than that at the Kaweka forest soil as observed for resin-P_i concentration (Figure 3.3). The reasons for these results have already been presented under the section on resin-P_i (3.4.1.1).

At both trial sites, the magnitude of increase in Bray-2 P concentrations due to the addition of TSP was greater than that for the corresponding rates of BGPR as observed for resin-P_i concentrations (section 3.4.1.1). This is due to the higher solubility of TSP compared with BGPR.

At the Kinleith forest, Bray-2 P concentration in the weed plots was significantly ($p<0.05$) higher than that in the weed-free plots in both years of the study (Figure 3.12). But there was no significant difference in Bray-2 P concentrations between the weed and weed-free plots at the Kaweka forest in either of the two years. These trends

are, in general, similar to those observed for resin-P_i concentrations (Figure 3.4). The reasons for these trends were given under the section on resin-P_i concentrations (section 3.4.1.1).

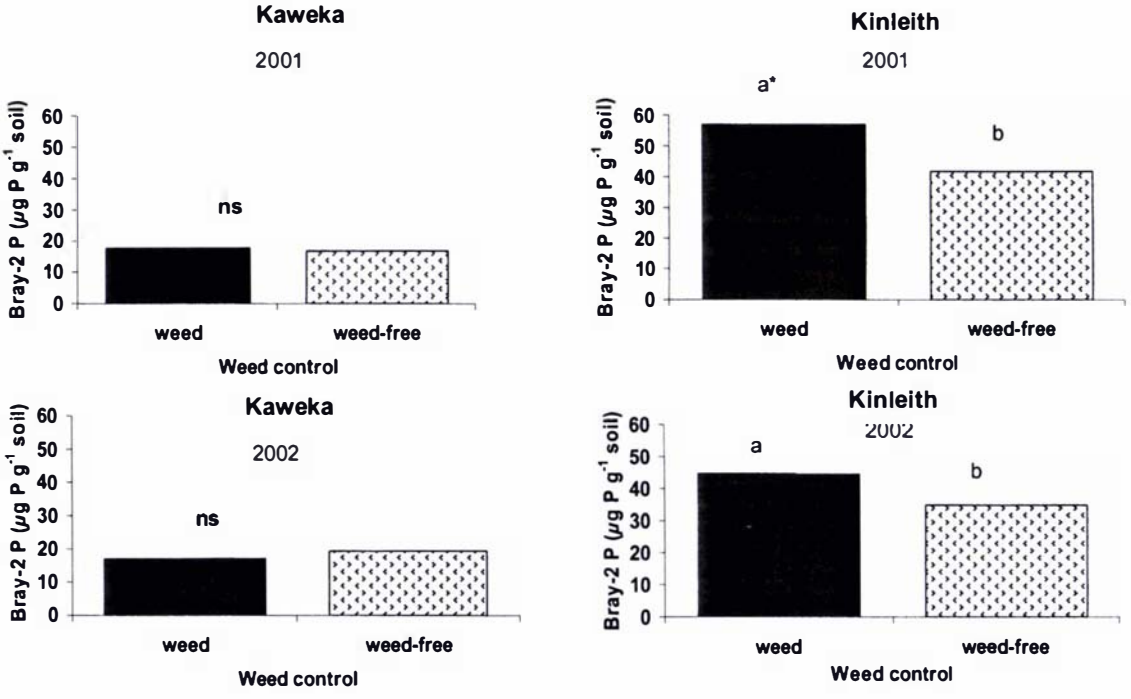

Figure 3.12 Effect of weed control on Bray-2 P concentrations after 1 and 2 years of weed control treatment (2001 and 2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
Statistical analysis was carried out on $\log_e$ transformed data for the Kinleith forest for both years
*Bars having same letters at the top are not different at $P<0.05$

Bray-2 P concentrations had a very strong relationship with resin-Pi, NaOH-P_i and H_2SO_4-P_i concentrations (Tables 3.5 and 3.6). This is consistent with the findings of many others that the Bray-2 extractant solubilises P associated with Fe and Al (NaOH-P_i), Ca (H_2SO_4-P_i) (Kadeba and Boyle, 1978; Mehlich, 1978; Cornforth *et al.*, 1983; Mackay *et al.*, 1984; Hahne *et al.*, 1988; Bationo *et al.*, 1991; Saggar *et al.*, 1992) and labile P (resin-P_i) (Saggar *et al.*, 1992). Because of the strong relationship of Bray-2 P concentrations with resin-P_i, NaOH-P_i, and H_2SO_4-P_i concentrations, the effect of

increased P rates on Bray-2 P concentrations was similar to that observed for these soil P fractions (see corresponding previous sections in this chapter).

Table 3.5 Correlation matrix for Bray-2 P concentrations and P fraction concentrations for all rates of (a) TSP and (b) BGPR after 2 years of treatment application (2002) in an Allophanic Soil (Kaweka) in a field trial (numbers in the table are correlation coefficients)

	Bray-2 P	**Resin-P_i**	**NaOH-P_i**	**NaOH-P_o**	**H_2SO_4-P_i**	**Residual-P**
			(a)			
Bray-2 P	1					
Resin-P_i	0.97***	1				
NaOH-P_i	0.95***	0.86**	1			
NaOH-P_o	0.78*	0.78*	0.64	1		
H_2SO_4-P_i	0.92**	0.84**	0.95***	0.75*	1	
Residual-P	0.44	0.45	0.44	0.14	0.40	1
			(b)			
Bray-2 P	1					
Resin-P_i	0.90**	1				
NaOH-P_i	0.87**	0.66	1			
NaOH-P_o	-0.05	0.07	0.00	1		
H_2SO_4-P_i	0.97***	0.80*	0.93**	-0.13	1	
Residual-P	0.78*	0.74*	0.51	-0.35	0.76*	1

* Correlation coefficient significant at $P<0.05$
** Correlation coefficient significant at $P<0.01$
*** Correlation coefficient significant at $P<0.001$

Table 3.6 Correlation matrix for Bray-2 P and P fractions for all rates of (a) TSP and (b) BGPR after 2 years of treatment application (2002) in a Pumice Soil (Kinleith) in a field trial (numbers in the table are correlation coefficients)

	Bray-2 P	**Resin-P_i**	**NaOH-P_i**	**NaOH-P_o**	**H_2SO_4-P_i**	**Residual-P**
			(a)			
Bray-2 P	1					
Resin-P_i	0.87**	1				
NaOH-P_i	0.99***	0.66	1			
NaOH-P_o	0.30	0.32	0.25	1		
H_2SO_4-P_i	0.91**	0.63	0.96***	0.26	1	
Residual-P	-0.24	-0.28	-0.32	0.08	-0.36	1
			(b)			
Bray-2 P	1					
Resin-P_i	0.92**	1				
NaOH-P_i	0.76*	0.52	1			
NaOH-P_o	0.23	0.18	0.53	1		
H_2SO_4-P_i	0.92**	0.75*	0.86**	0.44	1	
Residual-P	0.70	0.79*	0.39	0.05	0.39	1

* Correlation coefficient significant at $P<0.05$
** Correlation coefficient significant at $P<0.01$
*** Correlation coefficient significant at $P<0.001$

3.4.3.2 Olsen P

The Olsen P test is not commonly used for determining soil P availability to forest trees, but it is the main soil P test used on pastoral soils (Grigg, 1977; Cornforth *et al.*, 1983; Saggar *et al.*, 1992, 1999; Sinclair *et al.*, 1997) in New Zealand and numerous

data on this test are available in the literature on New Zealand soils. Therefore, this test was also used in the current study, but only for the soil samples collected in 2002.

The main effect of P fertiliser rates on Olsen P concentrations in the soil at the Kaweka forest and the Kinleith forest was significant ($p<0.0001$ and $p=0.0473$, respectively). There was also a significant ($p=0.0247$ and $p=0.0010$, respectively) effect for weed control on Olsen P concentrations at both trial sites. There was no interaction between P fertiliser rates and weed control on Olsen P concentration at the Kaweka forest, but it was significant at the Kinleith forest ($p=0.0090$). Most of these results are similar to those obtained for Bray-2 P and resin-P_i concentrations.

Increased rates of TSP application increased Olsen P concentrations but increased rates of BGPR application had no effect on Olsen P concentrations at both sites (Figure 3.13). Unlike the acidic Bray test, which extracts H_2SO_4-P_i, NaOH-P_i and resin-P_i, the alkaline Olsen test ($NaHCO_3$ pH 8.5) extracts only resin-P_i, NaOH-P_i and some NaOH-P_o (Thomas and Peaslee, 1973; Mackay *et al.*, 1984; Kumar *et al.*, 1991; Perrott *et al.*, 1989, 1992; Saggar *et al.*, 1992). The Olsen test does not extract H_2SO_4-Pi. The reason for BGPR increasing Bray-2 P but not Olsen P is that BGPR addition mainly increases H_2SO_4-P_i (Figure 3.8), which was extracted by the Bray test but not by the Olsen test. This is consistent with the absence of any correlation between Olsen P concentrations and H_2SO_4-P_i concentration when BGPR was applied, but when TSP was applied the correlation was significant (Table 3.7 and 3.8). Bray-2 P concentrations, on the other hand, had a significant correlation with H_2SO_4-P_i concentrations for both TSP and BGPR treatments (Table 3.5 and 3.6).

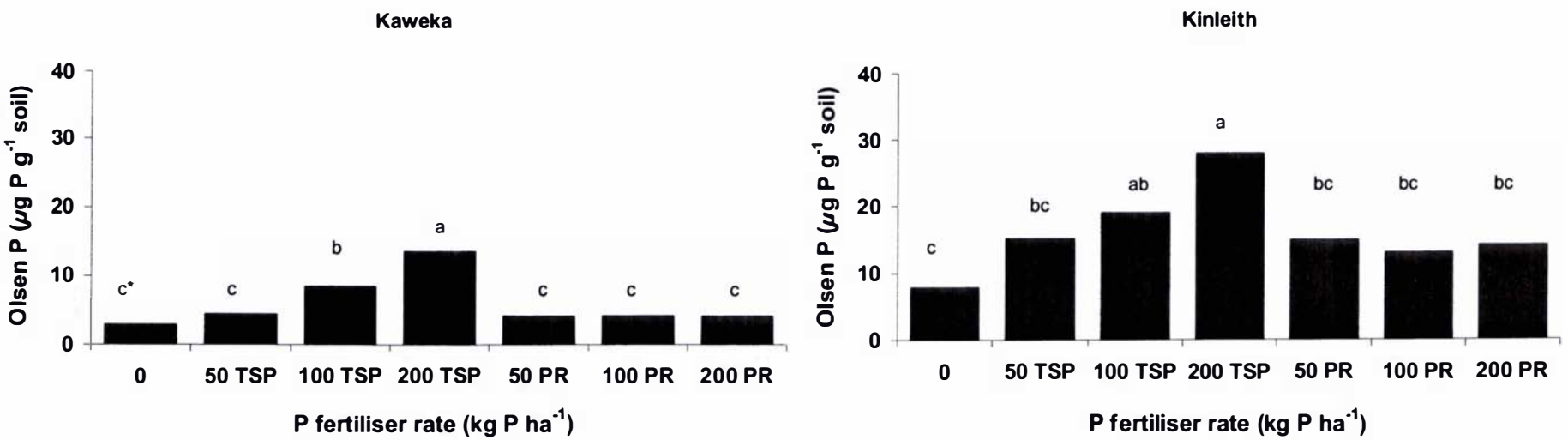

Figure 3.13 Effect of P fertiliser rates on Olsen P concentrations after 2 years of P application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
Statistical analysis was carried out on $\log_e$ transformed data for the Kaweka forest
*Bars having the same letters at the top are not different at $P<0.05$

Table 3.7 Correlation matrix for Olsen P concentrations and P fraction concentrations for all rates of (a) TSP and (b) BGPR after 2 years of treatment application (2002) in an Allophanic Soil (Kaweka) in a field trial (numbers in the table are correlation coefficients)

	Olsen P	Resin-P_i	NaOH-P_i	NaOH-P_o	H_2SO_4-P_i	Residual-P
			(a)			
Olsen P	1					
Resin-P_i	0.97***	1				
NaOH-P_i	0.94***	0.86**	1			
NaOH-P_o	0.78*	0.78*	0.64	1		
H_2SO_4-P_i	0.93**	0.84**	0.95**	0.75*	1	
Residual-P	0.47	0.45	0.44	0.14	0.40	1
			(b)			
Olsen P	1					
Resin-P_i	0.87**	1				
NaOH-P_i	0.42	0.66	1			
NaOH-P_o	0.48	0.07	0.00	1		
H_2SO_4-P_i	0.49	0.80*	0.93**	-0.13	1	
Residual-P	0.40	0.74*	051	-0.35	0.76*	1

* Correlation coefficient significant at $P<0.05$
** Correlation coefficient significant at $P<0.01$
*** Correlation coefficient significant at $P<0.001$

Table 3.8 Correlation matrix for Olsen P concentrations and P fraction concentrations for all rates of (a) TSP and (b) BGPR after 2 years of treatment application (2002) in a Pumice Soil (Kinleith) in a field trial (numbers in the table are correlation coefficients)

	Olsen P	Resin-P_i	NaOH-P_i	NaOH-P_o	H_2SO_4-P_i	Residual-P
			(a)			
Olsen P	1					
Resin-P_i	0.98***	1				
NaOH-P_i	0.79*	0.66	1			
NaOH-P_o	0.27	0.32	0.25	1		
H_2SO_4-P_i	0.75*	0.63	0.96**	0.26	1	
Residual-P	-0.25	-0.28	-0.32	0.08	-0.36	1
			(b)			
Olsen P	1					
Resin-P_i	0.83*	1				
NaOH-P_i	0.34	0.52	1			
NaOH-P_o	-0.25	0.18	0.53	1		
H_2SO_4-P_i	0.45	0.75*	0.86**	0.44	1	
Residual-P	0.70	0.83*	0.44	0.29	0.65	1

* Correlation coefficient significant at $P<0.05$
** Correlation coefficient significant at $P<0.01$
*** Correlation coefficient significant at $P<0.001$

The results of this study are consistent with the findings of others who investigated the suitability of the Olsen P soil test for pasture when PR was used. Saggar *et al.* (1992) reported that incubation of a range of PRs and MCP with four New Zealand soils increased Bray-1 P concentrations in all soils, whereas Olsen P concentrations

increased only in the MCP treated soils. They explained the inability of the Olsen P to increase in response to the addition of PRs as due to the inability of the alkaline Olsen P extractant ($NaHCO_3$ pH 8.5) to dissolve the residual PRs. The acidic Bray-1 P extractant dissolved the FPR in soils and, therefore, Bray-1 P concentrations increased with the addition of PRs. Mackay *et al.* (1984) also found that when different rates of superphosphate or Chatham Rise phosphorite (CRP) were added to soils at four sites in the Central North Island of New Zealand, Olsen P concentrations in soils did not increase with the increasing rates of CRP added in three of the four soils, but Bray P concentrations increased with increasing CRP rates in all four soils. However, Perrott *et al.* (1992) compared the effect of TSP and Sechura PR on Olsen P concentration at eight sites in New Zealand and reported that after six years of annual fertiliser application the Olsen P concentrations for both TSP-treated and SPR-treated plots increased with the increased fertiliser rate. But, at most sites, Olsen P concentrations increases for TSP treatments were higher than those for SPR treatments. Perrott *at al.* (1992) also stated that the Olsen P test underestimated the P status of the Sechura PR-treated soils because this test did not extract any of the residual apatite of the PR.

As observed for the resin-P_i concentrations in 2002, the Olsen P concentrations in 2002 at the Kaweka forest weed plots were significantly ($p<0.05$) lower than in the weed-free plots and at the Kinleith forest the weed plots had Olsen P concentrations that were significantly ($p<0.05$) higher than those in the weed-free plots (Figure 3.14). The reasons for this have already been discussed in the section on resin-P_i (3.4.1.1).

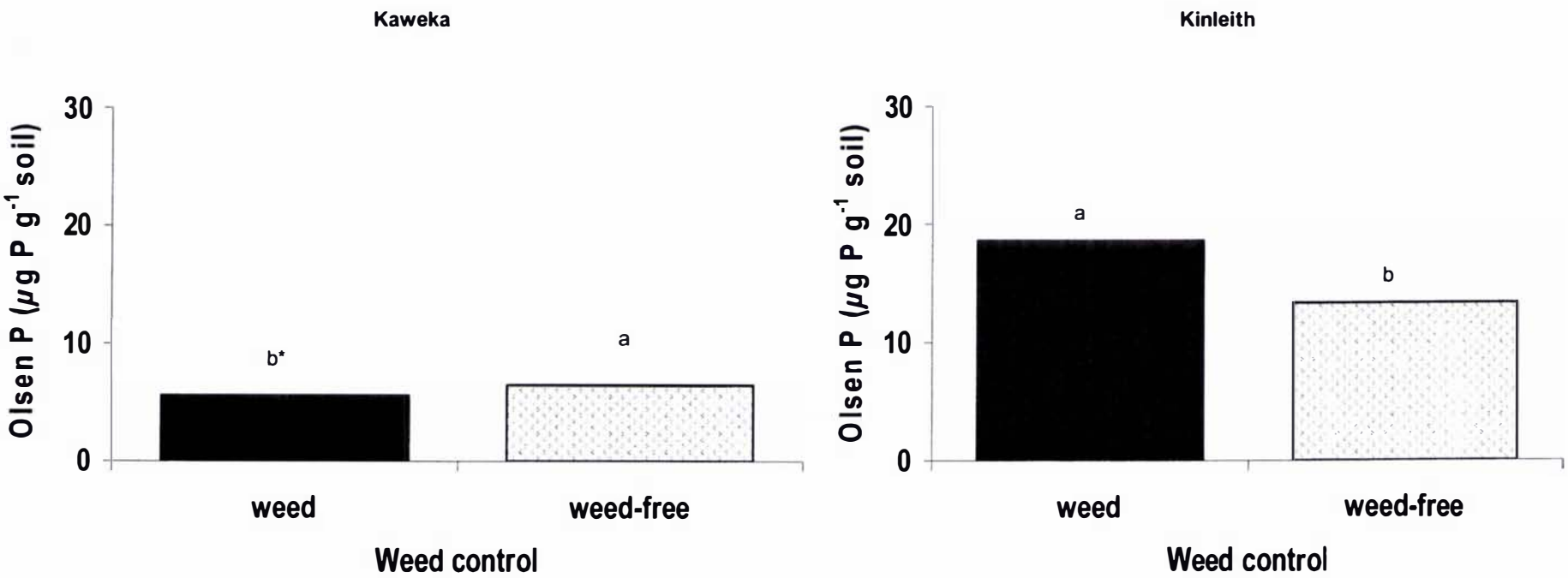

Figure 3.14 Effect of weed control on Olsen P concentrations after 2 years of weed control application (2002) in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
Statistical analysis was carried out on $\log_e$ transformed data for the Kaweka forest
*Bars having the same letters at the top are not different at $P<0.05$

There was a significant (p<0.0090) interaction between P fertiliser rates and weed control on Olsen P concentrations in the Kinleith forest soils (Table 3.9). At low P rates (0 and 50 kg P ha^{-1} of TSP and 50 and 100 kg P ha^{-1} of BGPR), there was no difference in Olsen P concentrations between weed and weed-free plots, while at high P rates (100 and 200 kg P ha^{-1} of TSP and 200 kg P ha^{-1} of BGPR), Olsen P concentrations in weed plots were significantly higher than those in weed-free plots. Therefore, the main effects of weeds (Figure 3.14) are a reflection of the weed effects at high P rates. The same pattern of interactions was observed for resin-P_i concentrations in 2001 but not for Bray-2 P concentrations. The reasons for this interaction were given under the discussion on resin-P_i (section 3.4.1.1).

Table 3.9 Effect of interaction between P fertiliser rates and weed control on Olsen P concentrations after 2 years of treatment application (2002) in a Pumice Soil (Kinleith) in a field trial

P fertiliser rate (kg P ha^{-1})	Weed control	
	Weed	Weed-free
	..... $\mu g\ P\ g^{-1}$ soil	
0	8.4 a C*	7.3 a A
50 TSP	12.9 a BC	17.5 a A
100 TSP	23.7 a B	14.4 b A
200 TSP	36.7 a A	19.2 b A
50 BGPR	17.8 a BC	12.1 a A
100 BGPR	13.0 a BC	13.2 a A
200 BGPR	18.4 a BC	10.0 b A

*Numbers within the same column followed by the same capital letters (P rate) or within the same row followed by the same lower case letters (weed control) are not significantly different at P<0.05

3.4.4 Downward movement of fertiliser P

At both forests, the application of 200 kg P ha^{-1} as TSP significantly increased both Bray-2 P and Olsen P concentrations at the 0-10 cm soil depth. The application of 200 kg P ha^{-1} as BGPR significantly increased only the Bray-2 P concentrations (Tables

3.11 and 3.12; Figures 3.15 and 3.16). At the 10-20 cm soil depth, however, the application of any of the two P fertilisers at the rate of 200 kg P ha^{-1} had no significant effect on Bray-2 P and Olsen P concentrations at the Kaweka forest, while at the Kinleith forest the two P fertilisers significantly increased Bray-2 P concentrations and TSP significantly increased Olsen P concentrations. There was no fertiliser effect on these P concentrations at the 20-30 cm soil depth at both sites (Tables 3.10 and 3.11; Figures 3.15 and 3.16).

In the Pumice Soil at the Kinleith forest, P from both TSP and BGPR has leached to the lower depth. In the less porous and higher P fixing Allophanic Soil at the Kaweka forest it might have been difficult for the fertiliser P to have moved to below 10 cm depth. The movement of P in Kinleith forest was higher for TSP than BGPR because of higher solubility of TSP.

Table 3.10 Bray-2 P concentrations in the soil profiles after 2 years of application of 200 kg P ha^{-1} in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

Soil depth (cm)	Kaweka forest			Kinleith forest		
	C	TSP	BGPR	C	TSP	BGPR
	..... $\mu g\ P\ g^{-1}$ soil					
0-10	6.2	33.3	26.7[1]	15.4	69.2	47.5
	B	A	A	B	A	A[2]
10-20	2.9	4.6	3.4	7.4	20.8	9.2
	A	A	A	C	A	B[2]
20-30	1.8	2.7	2.0	3.9	5.1	5.0
	A	A	A	A	A	A

C = control (no P applied)

[1]Numbers within the same row and trial site followed by the same letters are not different at $P<0.05$

[2]Statistical analysis was carried out on $\log_e$ transformed data

Table 3.11 Olsen P concentrations in the soil profiles after 2 years of application of 200 kg P ha^{-1} in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

Soil depth (cm)	Kaweka forest			Kinleith forest		
	C	TSP	BGPR	C	TSP	BGPR
	..... $\mu g\ P\ g^{-1}$ soil					
0-10	2.9	13.5	4.2[1]	7.9	27.9	14.2
	B	A	B[2]	B	A	B
10-20	1.1	2.0	1.3	2.9	8.4	4.4
	A	A	A	B	A	AB[2]
20-30	1.0	1.1	0.7	1.4	2.8	2.5
	A	A	A	A	A	A

C = control (no P applied)

[1]Numbers within the same row and trial site followed by the same letters are not different at $P<0.05$

[2]Statistical analysis was performed on $\log_e$ transformed data

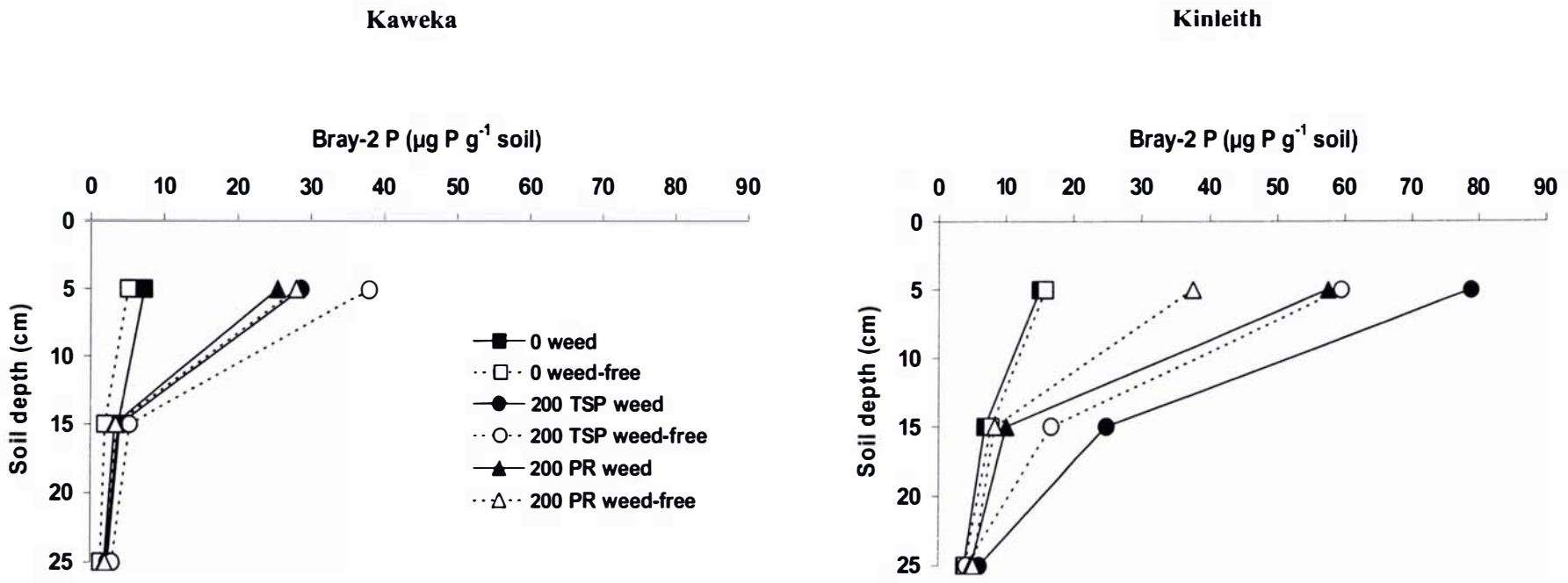

Figure 3.15 Distribution of Bray-2 P concentrations in the soil profiles after 2 years of application of 200 kg P ha^{-1} in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

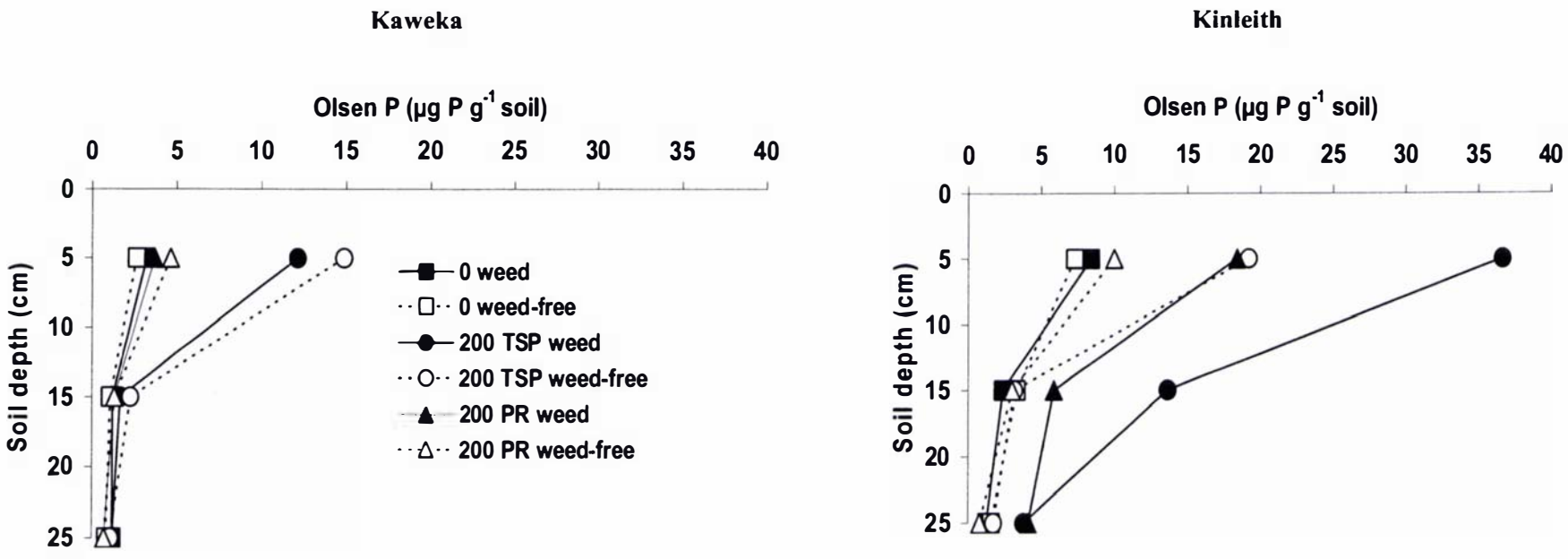

Figure 3.16 Distribution of Olsen P concentrations in the soil profiles after 2 years of application of 200 kg P ha^{-1} in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

As the soils from treatments receiving lower rates of P fertiliser were not analysed it is not known whether P would have moved below 10 cm depth at lower rates of P application.

The results in the current study are consistent with the findings from other studies. Hunter and Hunter (1991) studied the P movement in soils having different P retention capacities (0, 48, and 93%, a Tangitiki sand-Te Kopuru sand complex, a Waikare silt loam-Okaka clay and silty clay complex, and a clay derived from old deeply weathered volcanic ash soils, respectively) treated with rock phosphate and superphosphate at the rate of 150 kg P ha^{-1}. They reported that seven years after fertiliser application, at the site with 0% P retention, the plant-available P, as measured by Bray-1 P, was higher in fertiliser treated soils than in the untreated soils and this extended down to 60 cm, suggesting that P from the fertiliser has moved to 60 cm depth. This P movement was greater for the superphosphate treatment than for the rock phosphate treatment. At the site with 48% P retention, fertiliser P moved down to only 30 cm, while at the site with very high P retention (93%) there was no evidence of P movement below 10 cm. Humphreys and Pritchett (1971) studied the P movement in some sandy soils under slash pine (*Pinus elliottii* Engelm. var. *elliottii*) treated with superphosphate and Florida rock phosphate and reported that 7 to 11 years after fertiliser application, P from superphosphate was completely leached from the top 20 cm of soils with no P sorption or buffering capacity (Ground water Podzols), while in a soil with a high P sorption or buffering capacity (a Low Humic Gley) most of the P added was retained in the top 20 cm. In contrast, most of the P derived from rock phosphate was still retained in the top 20 cm even in the soil with no P sorption capacity.

3.5 Conclusions

The P fraction containing the largest percentage of soil P was the 0.1 M NaOH extractable P_o in the surface soils (0-10 cm soil depth) at the two second rotation forests. Therefore, the long-term P supplying power of the soil largely depends on the mineralisation of this organic P.

Changes in the concentration of P fraction as a result of P fertiliser application depend on the P fertiliser type. The rate of increase of the concentrations of the P fractions was highest for NaOH-P_i when TSP was applied and highest for H_2SO_4-P_i when BGPR was applied to both the Pumice and Allophanic Soils. The largest pool of P, NaOH-P_o, was unaffected by the P fertiliser application. NaOH-P_i increase was higher at the Kaweka forest than that at the Kinleith forest probably because of the higher P fixation in the Allophanic Soil at the Kaweka forest. Both type of fertiliser increased plant-available soil P as measured by resin-P_i and Bray-2 P.

The effect of weeds on plant-available soil P concentration depends on the type weeds and the degree of P deficiency in the soil. The deeper root systems of the Himalayan honeysuckle, buddleia and some toetoe at the Kinleith forest enhanced the plant-available P concentrations in soil surface probably by removing P from the subsoils and returning it in the form of litter to the soil surface (pumping mechanism). At the P-deficient Kaweka forest soils, however, the weeds reduced resin-P_i and Olsen P concentrations. This suggests that when plant-available P is very low, the weeds tend to compete with radiata for P.

Fertiliser-P from TSP and BGPR application can move to below 10 cm soil depth within 2 years of application in Pumice Soil but not in the higher P fixing Allophanic Soil.

Attempts have been made to use the results reported in this chapter to explain the growth and P concentrations in the needles of radiata in the next chapter.

Chapter 4

Effect of P Fertilisers and Weed Control on Second-rotation *P. radiata* - Needle P Concentration and Tree Growth

4.1 Introduction

The results from Chapter 3 showed that in the P-deficient Kaweka forest soil (Bray-2 P 4 μg P g^{-1} soil) the application of triple superphosphate (TSP) and Ben-Geurier phosphate rock (BGPR) increased resin-P_i, NaOH-P_i and H_2SO_4-P_i concentrations. In the moderate P fertility Kinleith forest soil (Bray-2 P 13 μg P g^{-1} soil) the application of these P fertilisers increased only NaOH-P_i and H_2SO_4-P_i concentrations. At both forests, increased rates of TSP application increased the NaOH-P_i fraction at a faster rate than the other P fractions with the increase being more marked at Kaweka forest with the higher P fixing soil (92% P retention) than at Kinleith forest (83% P retention). In contrast, the addition of increased rates of BGPR application increased the H_2SO_4-P_i fraction at a faster rate than the NaOH-P_i fraction in both forests.

Unlike resin-P_i concentrations that increased with increased rates of application of both P fertilisers only at Kaweka forest, Bray-2 P concentrations increased with increasing rates of application of both P fertilisers in both forests. Olsen P concentration increased with increasing rates of TSP-P in both forests, but not with increasing rates of BGPR-P.

At the Kaweka site, the presence of weeds reduced resin-Pi concentration in the soil. But at the Kinleith forest the presence of weeds increased resin-P_i concentrations in the soil.

In this chapter, the effect of these changes in soil P concentrations on needle P concentrations and tree growth are presented. Attempts are also made to determine the relationships between plant-available soil P concentrations and needle P concentrations at each trial site. The results of this study are expected to give a better understanding of the response of needle P concentration and growth of radiata to different P sources and rates, and weed management.

4.2 Objectives

The objectives of the study reported in this chapter are:

1. To investigate the effect of different rates of two P fertilisers (TSP and Ben-Guerir phosphate rock) and weed control on the needle P concentrations and the growth of 4-5 year-old second-rotation *P. radiata* on an Allophanic Soil and a Pumice Soil.
2. To find the relationships of needle P concentrations with soil P fractions and plant-available soil P concentrations in the above trials.

4.3 Materials and methods

4.3.1 Trial design and conduct

The trial design and conduct were described in Chapter 3.

4.3.2 Foliage sampling and tree growth measurement

The sampling of the foliage was carried out by Forest Research Ltd., Rotorua. Foliage samples were collected from both trials in March 2003 (29 months after fertiliser and weed treatments). The needles from secondary branches in the upper third of the crown were randomly sampled from 10 trees in the weed sub-plot treatment, and from 5 trees

in the weed-free sub-plot treatment. Samples were oven dried at 70°C to constant weight then ground to <1 mm before chemical analyses.

In September 2002 (24 months after fertiliser and weed treatments), at both trial sites, height, diameter at breast height (DBH), and basal area (BA) were measured on 20 trees in the weed sub-plot treatment, while in the weed-free sub-plot, the measurements were taken from 5 trees (initial DBH and BA measurements were not made at both forests). 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 Kaweka forest and 670 stems ha^{-1} at Kinleith forest) at breast height, expressed in square metres (MacLaren, 1993).

4.3.3 Chemical analysis

The chemical analysis of the foliage was carried out by Forest Research Ltd, Rotorua. External standards were used along with trial samples during foliage-P and N-analysis.

Foliage-P analysis

Five ml of concentrated HNO_3 (99%) was added to 0.25 g of dried and ground foliage in a Pyrex tube and digested at 150°C for about 20 minutes (until the digest was clear). After cooling, 1.5 ml of 30% H_2O_2 was added and the digestion continued for 1 hour. After further cooling, the sample was diluted with 25 ml of deionised water and the P concentration determined using inductively coupled plasma (ICP) spectrometry. All results were corrected to oven dry weights at 100°C (Leco Co., 1996).

Foliage-N analysis

Foliage samples, each weighing between 0.1 and 0.25 g were combusted in a ceramic boat in a stream of oxygen. The resulting gases (CO_2, SO_2, N_2 and NO_x) were passed over a Cu catalyst to convert NO_x to N_2. Nitrogen was determined by the thermal conductivity of the emerging gas stream (Leco Co., 1996).

4.3.4 Statistical analysis

Analysis of variance (ANOVA) for a split-plot design was performed using SAS (SAS Institute, 2001). The least significant difference (LSD) test at $P<0.05$, unless otherwise stated, was used to separate the means when analysis of variance (ANOVA) results indicated that there were significant treatment effects (Steel *et al.*, 1997). Unlike the data for soil P concentrations, the data for herbage P concentrations and growth conformed to the assumptions (in particular, the homogeneity of variance and normality) underlying the ANOVA. Therefore, no transformation of the data was made.

4.4 Results and discussion

4.4.1 Needle P concentration

Application of both P fertilisers significantly ($p<0.0001$, $p<0.0041$, respectively) increased needle P concentrations at the Kaweka and Kinleith forests (Table 4.1). Neither weed control nor interaction between P fertiliser rates and weed control had significant effects on needle P concentrations at both sites.

Table 4.1 Needle P concentrations (%) after 29 months of P fertiliser application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

P fert. rate (kg P ha^{-1})	Kaweka	Kinleith
0	0.136 d*	0.124 c
50 TSP	0.159 c	0.149 bc
100 TSP	0.175 ab	0.169 ab
200 TSP	0.188 a	0.188 a
50 BGPR	0.160 c	0.149 bc
100 BGPR	0.165 bc	0.150 b
200 BGPR	0.163 bc	0.165 ab

*Numbers within the same column followed by the same letters are not different at $P<0.05$

At both Kaweka and Kinleith forests, the needle P concentrations in the control treatment (no P fertiliser added) soil were approximately at the level considered satisfactory for the growth of radiata (0.13% foliar P, Mead and Gadgil, 1978; Will, 1978) (Table 4.1). However, the Bray-2 P concentration in soils at Kaweka forest (0-10 cm soil depth) (6 μg P g^{-1} soil, Chapter 3) was below the critical concentration of 12 μg P g^{-1} soil (Ballard, 1974), while at Kinleith forest (15 μg P g^{-1} soil, Chapter 3) it was above the critical P concentration.

At both forests, the application of BGPR beyond the 50 kg P ha^{-1} rate had no significant effect on needle P concentration (Table 4.1 and Figure 4.1). But the application of TSP at 200 kg P ha^{-1} produced higher needle P concentration than the application of TSP at 50 kg P ha^{-1}. At both forests, the needle P concentration obtained from the application of BGPR at the rate of 50 kg P ha^{-1} was equal to that from the application of TSP at the same rate, 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 (NZ\$1.26 kg^{-1} P – ground cost price in July 2004) can be used to maintain satisfactory needle P concentration, instead of the more expensive manufactured P fertiliser, triple superphosphate (NZ\$2.05 kg^{-1} P– ground cost price in July 2004), in these acidic soils for at least 2 years after fertiliser application (the duration of the trial).

The needle P concentrations for the application of BGPR at the rates beyond 50 kg P ha^{-1} were slightly lower than that for 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 for maintaining satisfactory needle P concentration for the first two years after fertiliser application, because the needle P concentration at these P rates were higher than the critical P concentrations considered necessary to produce maximum tree growth.

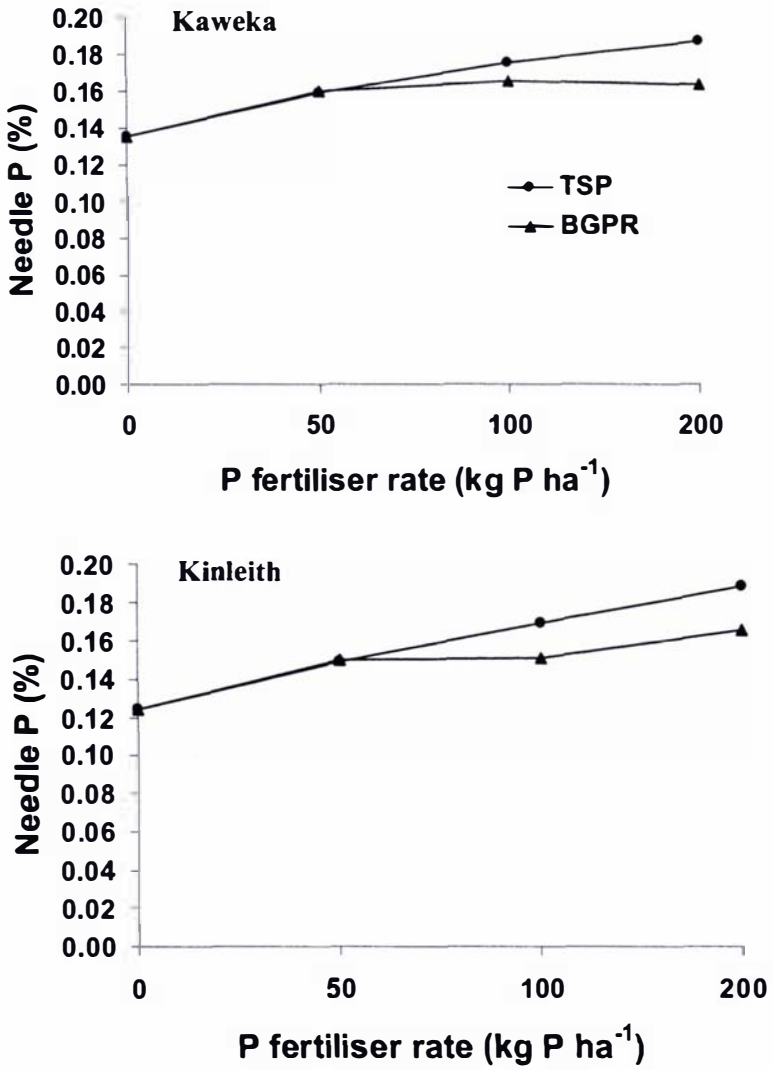

Figure 4.1 Changes in needle P concentrations with increasing rates of TSP and BGPR after 29 months of treatment application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in a field trial

Other studies have also shown that the more soluble superphosphate fertiliser was more effective than phosphate rock fertiliser in increasing needle P concentrations. Hunter and Graham (1983) studied the response of radiata pine (4- to 7-year-old stands) to the application of single superphosphate and three phosphate rocks (A grade rock, C grade rock and "citraphos" from Christmas Island) at the rates of 0, 75, and 150 kg P ha^{-1} to

three P deficient soils (Bray P 1-2 μg P g^{-1} soil) of contrasting P retention capacities (P retention 93%, 48%, and 0%; soil pH 5.4, 4.9, and 4.5, respectively) in the North Island of New Zealand. They reported that three years after P application, the effectiveness of the fertilisers in increasing needle P concentration in all three soils decreased in the order, superphosphate ≥A grade rock ≥citraphos > C grade rock. This order of decreasing effectiveness of the fertilisers followed the same order as the solubilities of these fertilisers in 2% citric acid.

Mead (1974) also studied the response of radiata pine (7-year-old stand) to single superphosphate and Christmas Island 'C' phosphate fertilisers on another P-deficient soil (P retention 40%, pH 4.7) at Maramarua forest in the North Island of New Zealand. No soil P test value for this site was reported. The trial had four 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 before applying fertilisers (0.081-0.086% P). The P fertiliser treatments had no significant effect on the needle P concentrations after 2, 4, and 6 years. However, the P fertiliser treatments showed a significant effect on the needle P concentration after 8 years. The mean needle P concentrations for the 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 response to P fertiliser application from the second 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.

Based on the needle P concentration values it could be inferred that the trees at Kaweka and Kinleith forests in this study were less P deficient (Table 4.1) than those of Mead (1974) at Maramarua forest. Therefore, P application at Kaweka and Kinleith forests, at rates similar to those used at Maramarua forest have produced needle P concentrations higher than the critical P concentrations at Kaweka and Kinleith forests, whereas this was not the case at Maramarua forest.

There was no significant effect of weed control on needle P concentrations, either at Kaweka forest or at Kinleith forest. This did not reflect the significant changes in the soil P concentrations at 0-10 cm depth caused by the weed treatment (Chapter 3). At Kaweka forest, weed-free plots had significantly higher plant-available soil P concentrations (resin-P_i and Olsen P) than weed plots, while, at Kinleith forest, weed plots had significantly higher plant-available soil P concentration (Bray-2 P, resin-P_i and Olsen P) than weed-free plots (Chapter 3). These results suggest that the significant differences in plant-available soil P concentrations observed in the 0-10 cm soil depth did not result in any significant impact on needle P concentrations. The differences in plant-available soil P concentrations due to the weed control treatment were observed only in the topsoil (0-10 cm soil depth) (Chapter 3), while tree roots were also taking up P from the subsoil below the 10 cm depth in both forest soils where there was no difference in plant-available soil P concentrations between the weed and the weed-free treatments (Chapter 3). Needle P concentrations, which are controlled by P uptake from both surface soil and subsoil, were therefore not different between weed and weed-free plots even though soil P concentrations at 0-10 cm depth were significantly different between these two plots. Mitchell *et al.* (2000) also reported that Mg fertiliser application to *P. radiata* on a Pumice Soil at Kaingaroa forest in the North Island of New Zealand had significant effect on soil Mg concentrations in the top soil (0-10 cm) but it had very little effect on needle Mg concentrations. They too suggested that this was due to the tree roots probably taking up Mg from soil layers below the 10 cm depth where the Mg fertiliser treatment had very little or no effect on soil Mg concentrations. Another reason for the weed treatment having significant effect on the plant-available soil P concentration but not on the needle P concentration could be that the trees are not severely P deficient to respond to small changes in soil P concentration.

4.4.2 Relationship between needle P concentrations and soil P concentrations

The P concentration in the needles was regressed against different plant-available soil P tests (Bray-2 P, Olsen P, resin-P_i fraction, and NaOH-P_i) at both sites. At both sites,

the needle P concentrations had significant logarithmic relationships with the four soil P tests 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, respectively at Kaweka forest and R^2 = 0.54, P<0.0001 for Bray-2 P; R^2 = 0.30, P=0.0002 for Olsen P; R^2 = 0.27, P=0.0005 for resin-P_i; R^2 = 0.26, P=0.0006 for NaOH-P_i, respectively for Kinleith forest) (Figures 4.2 and 4.3). The R^2 values for the relationships between needle P concentrations and soil P tests at Kinleith forest were lower than the corresponding R^2 values at Kaweka forest. One reason for this may be the higher initial plant-available P concentrations (Bray-2 P 15 μg P g^{-1} soil and resin-P_i 11 μg P g^{-1} soil at Kinleith forest compared to 6 μg P g^{-1} soil and 3 μg P g^{-1} soil at Kaweka forest) at the Kinleith site (Chapter 3) which would have meant that further increases in needle P concentrations with increasing soil test P values would have been small and variable.

At both sites, the R^2 values for the Bray-2 P test were the highest, indicating that the Bray-2 P soil test was the best for predicting soil P availability to radiata. The curvilinearity of the relationships, notably at Kaweka forest, indicates that the increase of needle P concentrations per unit increase of plant-available soil P diminishes with the increase in plant-available soil P concentrations.

The relationships between needle P concentrations and soil P concentrations may have been more accurate if soil bulk density differences in the various treatment plots were considered and soil P was expressed in soil volume basis to 10 cm soil depth, but unfortunately soil bulk density was not measured in every plot in this trial.

The needle P concentration had no relationship with NaOH-P_o suggesting that labile organic P is not controlling the variability of needle P concentrations.

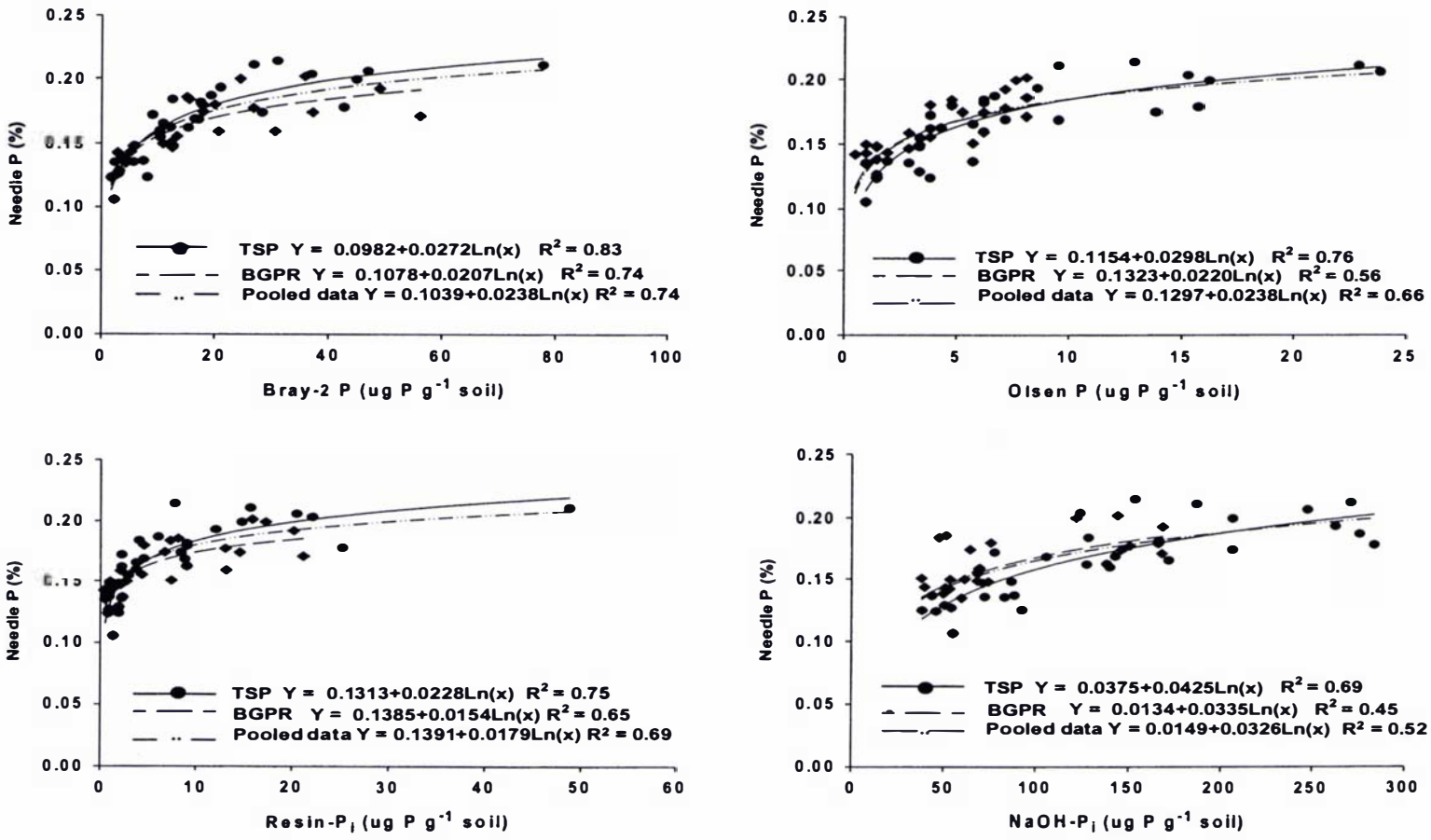

Figure 4.2 Relationships between needle P concentrations and P extracted by different plant-available soil P tests (Bray-2 P, Olsen P, resin-P_i, and NaOH-P_i concentrations) after 29 months of treatment application in an Allophanic Soil (Kaweka) in a field trial

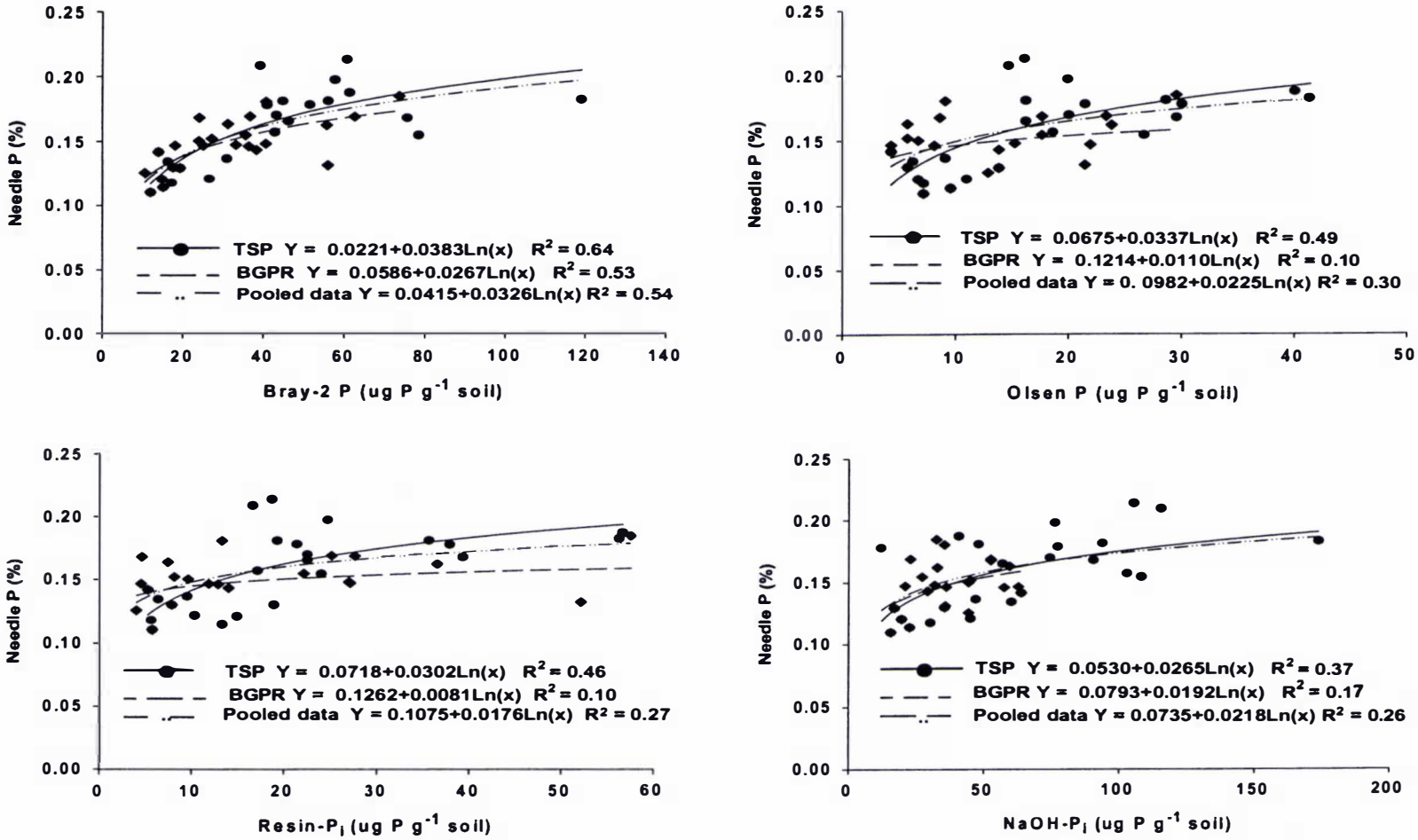

Figure 4.3 Relationships between needle P concentrations and P extracted by different plant-available soil P tests (Bray-2 P, Olsen P, resin-P_i, and NaOH-P_i concentrations) after 29 months of treatment application in a Pumice Soil (Kinleith) in a field trial

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 at both sites suggests that radiata trees are taking up P from one or more of the P pools, Ca-P, Fe-P and Al-P. The NaOH-P_i concentration which is a measure of P adsorbed to allophane and Fe and Al oxides, is also significantly related to needle P concentrations (Figures 4.2 and 4.3). But the H_2SO_4-P_i concentration which is a measure of P associated with Ca is only weakly related to needle P concentrations (Figure 4.4). Considering these relationships it appears that the trees were taking up P mainly from the pool of P adsorbed to Fe and Al oxides and allophane in these soils.

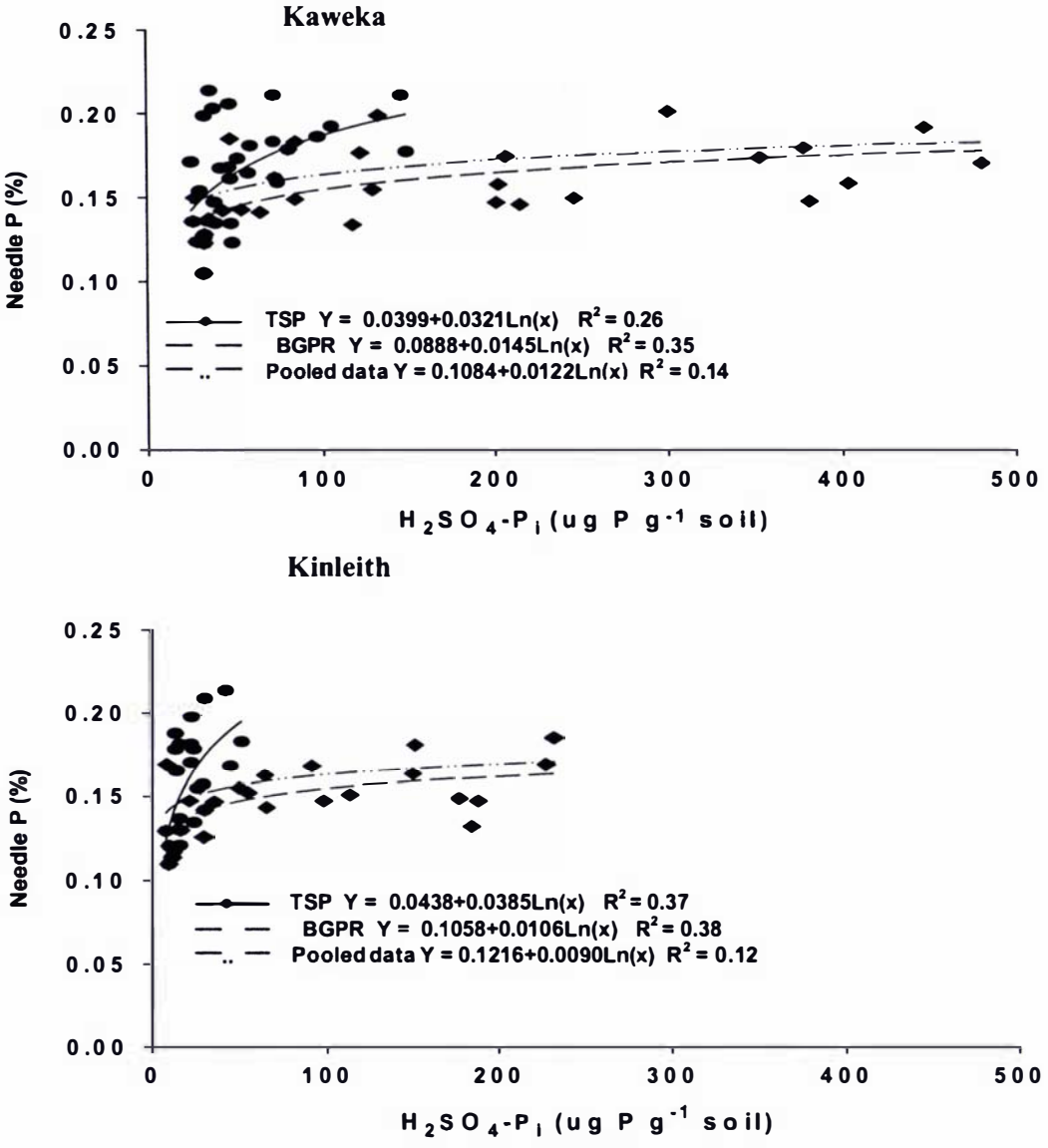

Figure 4.4 Relationships between needle P concentrations and the H_2SO_4-P_i concentrations after 29 months of treatment application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

4.4.3 Needle N concentration

The needle N concentrations at both forests were higher than the critical N concentration (1.2% N) (Will, 1985). Therefore, the trees were not considered to be N deficient. The effect of the P fertiliser rates on needle N concentration was not

significant at both forests. However, the effect of the weed control treatment on needle N concentrations was significant (p= 0.0058) at Kaweka forest but not at Kinleith forest (Figure 4.5). There was no interaction between P fertilisers and weed control on needle N concentration at both sites.

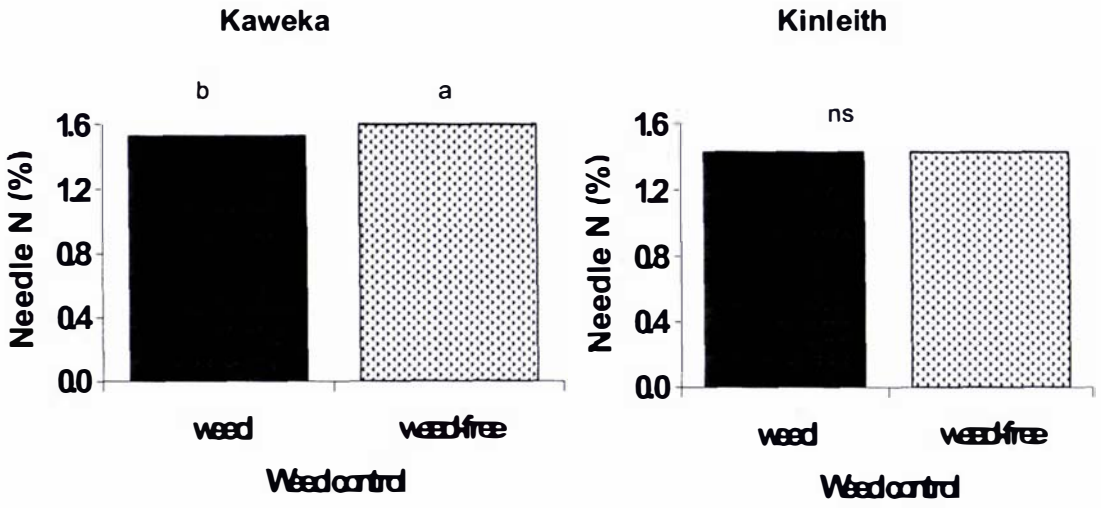

Figure 4.5 Effect of weed control on needle N concentration after 29 months of treatment application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
*Bars having the same letters at the top are not different at P<0.05

At Kaweka forest, weed removal significantly increased needle N concentrations (Figure 4.5). This is consistent with the 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 one year after transplanting of pine seedlings the removal of weeds, consisting of Yorkshire fog grass, sorrel, flatweed, bracken, subterranean clover, and ryegrass, significantly increased needle N, P and K concentrations. Clinton *et al.* (1994) who studied the effects of pasture on the nutrient uptake by 4-year-old radiata pines on a Templeton silt loam, Rangiora, New Zealand, also reported that removal of pasture (perennial ryegrass, white clover and cocksfoot) significantly increased radiata needle

N, P and Mg concentrations (by 65, 74, and 76%, respectively). Watt *et al.* (2003c) investigated the effect of weed competition on the growth of 1-year-old *P. radiata* seedlings in a dryland site on a Lismore stony silt loam at Christchurch, New Zealand. They reported that the mean *P. radiata* needle N concentration in plots without broom was 1.7%, compared to 1.4% in plots with broom, in spite of the broom-fixing atmospheric N_2. The N uptake by radiata pine in the plots without broom was also much higher (18.7 kg ha^{-1}) than in the plots with broom (2.1 kg ha^{-1}).

In contrast to the above studies, Richardson *et al.* (1996) reported that the presence of grass, gorse, pampas, broom, buddleia, herbaceous broadleaves, and lotus under a three-year old *P. radiata* stand grown on a moderately fertile pumice soil under a moist environment at Rotorua slightly increased or had no effect on needle N concentrations. These results are similar to those obtained at Kinleith forest in the present study on the same type of soil, where weed-plots had slightly higher needle N concentration than weed-free plots, although this was not statistically significant. The slightly increased needle N concentrations in weed plots may be due to the higher plant-available soil P concentrations in weed-plots (Figure 3.12, Chapter 3) which may have helped N uptake by the trees (Adams and Walker, 1973; Gadgil *et al.*, 1992; Ndufa *et al.*, 1999; McGrath and McArthur, 1990).

The reason for the weed removal increasing needle N concentrations at the Kaweka forest but not at the Kinleith forest may be related to the differences in soil N concentrations and weed species and their population in the two forests.

The soils at Kaweka forest had lower concentrations of total soil N (0.27% N) than the soils at Kinleith forest (0.40% N) (Chapter 3). Therefore, the competition for N between weeds and *P. radiata* might have been higher at Kaweka forest than at Kinleith forest. The NO_3^- and NH_4^+ concentrations in the soils were not measured to determine whether there was any difference in plant-available N between the two soils. The biomass and N uptake of the weeds were also not measured in this study to evaluate whether there was any difference in weed competition for N in the two forests. The N input through N_2 fixation in the two forests is expected to be very small because there were no significant populations of N fixing legumes in the two forests.

4.4.4 Plant growth

4.4.4.1 Height

There was no tree height response to the P fertiliser treatments at both Kaweka and Kinleith forests 24 months after application of P fertilisers. But weed removal significantly (p=0.0102) increased tree height at Kinleith forest (Figure 4.6). There was no interaction between P fertiliser rates and weed control on tree height at both forests.

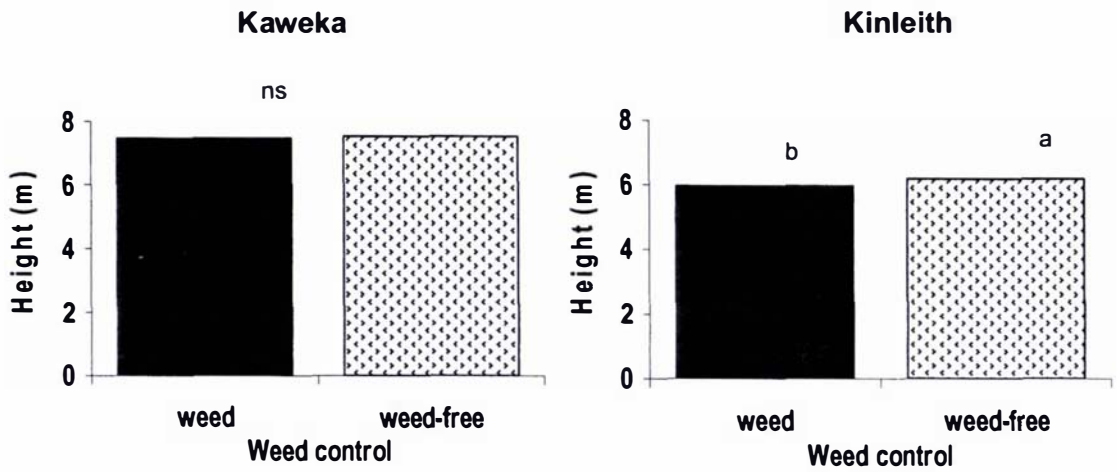

Figure 4.6 Effect of weed control on tree height after 24 months of treatment application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
*Bars having the same letters at the top are not different at P<0.05

Although the presence of weeds at Kaweka forest significantly reduced needle N concentrations, it did not suppress tree height (Figure 4.6). On the other hand, at Kinleith forest, the presence of weeds had no effect on needle N and P concentrations but significantly decreased tree height. At both sites, the needle N and P concentrations were higher than the concentrations of these elements required for maximum growth (Table 4.1 and Figure 4.5). Therefore, radiata growth was not likely to have been restricted by the lack of P or N. The lower tree height in the weed plots at Kinleith

forest was probably due to weeds competing for water and/or nutrients other than N and P.

Many studies have reported that weed removal increased the growth of radiata pine trees mostly resulting from elimination of competition for water between weeds and trees. Nambiar and Zed (1980) reported that 17 months after transplanting 10-month-old *P. radiata* seedlings at Mount Gambier, South Australia, the trees in weed-free plots were 3.9 times taller than those in heavily weed-infested plots. They explained this was due to weeds causing severe water stress as reflected in the more negative value of needle water potential in plots heavily infested with weeds (-2690 to -2910 kPa) than that in weed-free plots (-460 to -1060 kPa), and the reduction of needle nutrient (N, P and K) concentrations in radiata seedlings. Squire (1977) also reported that two years after planting of radiata seedlings on a Shelley sandy clay loam soil in the Koetong plantation in north-eastern Victoria, Australia, soil moisture competition by grass was the major factor restricting the height of radiata trees.

In New Zealand, Watt *et al.* (2003a) reported that 3 years after planting of *P. radiata* on a broom-free Lismore stony silt loam soil in a dryland site at Canterbury, the trees were 2 times taller than those planted in broom infested land. They found that the total annual evaporation in the plots with broom was 92 mm higher than in the plots without broom. This led them to suggest that the reduction in radiata pine growth in the presence of broom was mainly due to competition for water between radiata and broom. Even though broom fixed atmosphere N, it took up 29 kg N ha^{-1} per year from the soil which exceeded the rates of N transfer from broom to radiata (1 kg N ha^{-1} per year or 1% of the total N-fixed by the broom). Therefore, there was also some competition for N between broom and radiata. They reported that this may not have any influence on the height reduction in radiata because needle N concentrations in both broom and broom-free plots were higher than the N concentration corresponding to maximum tree yield. Richardson *et al.* (2002) also reported that the presence of broom reduced the height of 9- to 12-year-old *P. radiata* on a Pallic soil, on the Canterbury-Plains by reducing soil water availability in the root zone. They found that the annual integrated root-zone water deficit (total daily water deficit in the root-zone soil profile for a 12 month period)

in the plots with broom ranged from 1245 to 3188 mm, while in the plots without broom it ranged from 1024 to 2395 mm.

The radiata needle P concentrations at both Kaweka and Kinleith forests in the control treatment (no P fertiliser added) were approximately at the level considered satisfactory for the growth of radiata (0.13% foliar P, Mead and Gadgil, 1978; Will, 1978). This explains why there was no growth response to P fertiliser application in these forests. Hunter and Graham (1983) studied the growth response of 4-year-old radiata pine (foliage P concentration 0.010%) to the application of P fertilisers (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, Bray-1 P 2 μg P g^{-1} soil, P retention of 93%). They found that up to 3 years after P fertiliser application, there was no significant growth response to the treatments. Probably rapid response (in less than 2 years after P fertiliser application) to P fertiliser is possible only in soils which are severely P deficient and have low to medium P retention capacities. For example, Mead (1974) reported that 2 years after P fertiliser application (superphosphate – 52 kg P ha^{-1}, Christmas Island 'C' – 52 and 104 kg P ha^{-1}) the height of 7-year-old *P. radiata* stands significantly increased on a P-deficient clayey soil (with a medium P retention of 40%; foliage P concentration 0.065%) at Maramua forest.

4.4.4.2 Diameter at breast height (DBH)

The effects of P fertiliser rates on DBH at both forest sites are similar to those on tree height reported in the previous section. However, unlike the effect of weed control on tree height, which was significant only at Kinleith forest, the effect of weed control on DBH was significant at both forest sites (p=0.0458 for Kaweka forest, p=0.0030 for Kinleith forest). There was no interaction between P fertiliser rates and weed control on DBH as observed for tree height.

Weed removal significantly increased DBH at both Kaweka and Kinleith forests (Figure 4.7). The increase in DBH at both sites is probably related to the improvement in

growth promoting factors other than P and N by weed removal, especially the increase in water availability as discussed in section 4.4.4.1. Nambiar and Zed (1980) reported that water stress in *P. radiata* caused by the presence of weeds, such as Yorkshire fog grass, sorrel, flatweed, bracken, subterranean clover, and ryegrass (see section 4.4.4.1) dramatically reduced stem diameter of the trees even though a complete fertiliser was applied. They reported that the stem diameters in weed-free plots were 5.8 times higher than those in weed plots. Richardson *et al.* (2002) reported that the diameters of radiata pines were increased with the removal of broom and this was due to the increased soil water content in the root zone (see section 4.4.4.1). Meanwhile, Watt *et al.* (2003b) reported that in the second year after planting of radiata 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.

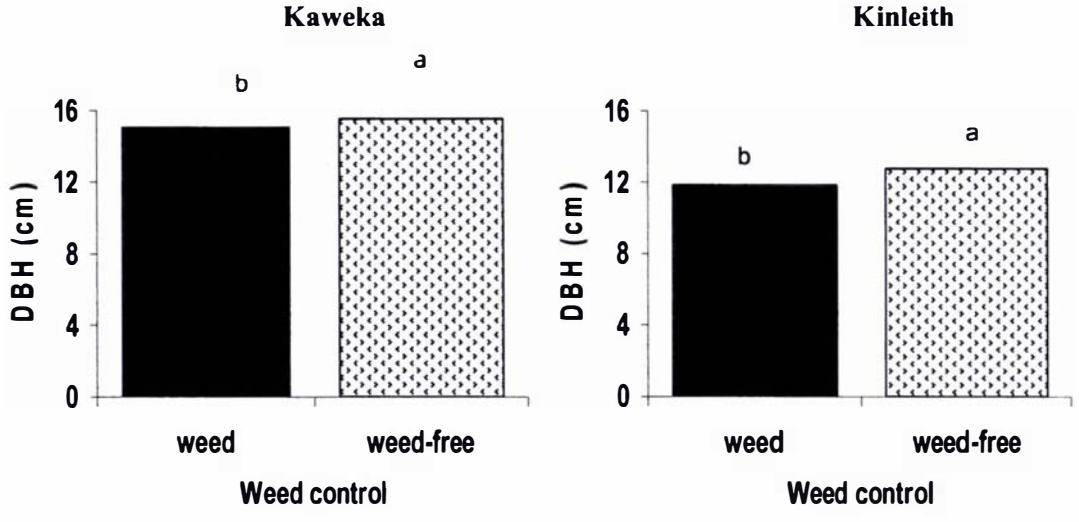

Figure 4.7 Effect of weed control on DBH after 24 months of treatment application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials

*Bars having the same letters at the top are not different at $P<0.05$

4.4.4.3 Basal area (BA)

As observed for DBH, BA at both sites was significantly (p=0.0014 for Kaweka forest, p=0.0079 for Kinleith forest) influenced by the weed control. As for height and DBH the P fertiliser rates had no effect on BA. There was also no interaction between P fertiliser rates and weed control on BA.

Basal area was significantly increased by weed removal at both forest sites (Figure 4.8). As in the case of DBH, the increase in BA is probably due to the increase in soil water availability during the dry season when weeds were removed. Watt e*t al.* (2003b) reported that 3 years after removal of broom, BA significantly increased compared to that in the presence of broom. The predawn water potential in the needles of radiata in the presence of broom was lower than that in radiata in the absence of broom (see section 4.4.4.2). They also reported that basal area was a more sensitive indicator of competition between radiata and broom compared with groundline diameter, height, and crown diameter. In their study, the basal area of the trees in broom-free plots increased 12-fold over the course of 3 years, while, in plots with broom the basal area increased only 2-fold. Richardson *et al.* (2002) also 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.

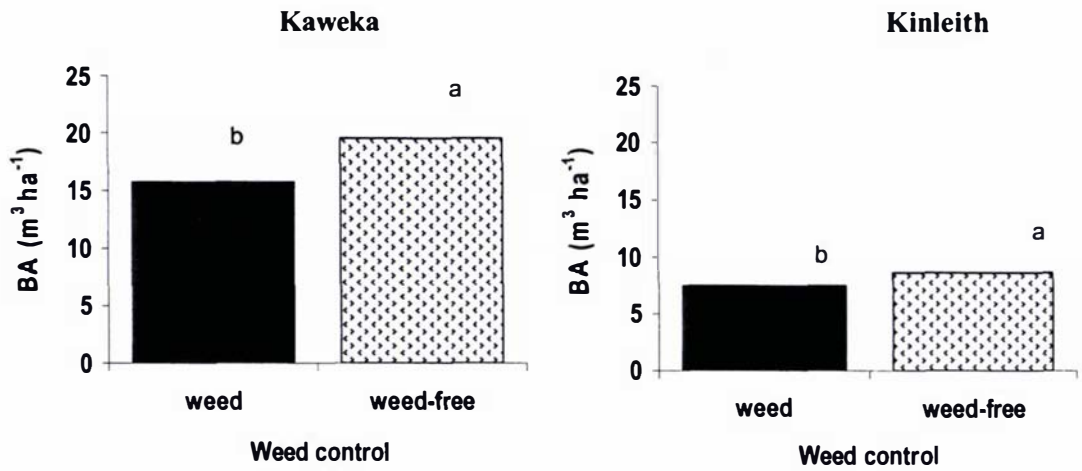

Figure 4.8 Effect of weed control on BA after 24 months of treatment application in an Allophanic Soil (Kaweka) and a Pumice Soil (Kinleith) in field trials
*Bars having the same letters at the top are not different at $P<0.05$

4.5 Conclusions

In both the Allophanic and Pumice Soils, needle P concentration of *P. radiata* can be predicted by soil tests, Bray-2 P, Olsen P, resin-P_i, and NaOH-P_i tests. Of these soil tests, Bray-2 P seems to be the best test in predicting soil P availability to radiata pine. The strong relationship between needle P concentration and the NaOH-P_i fraction and the weak relationship between needle P concentration and the H_2SO_4-P_i fraction suggest that radiata pine was probably taking up P more from P-adsorbed to allophane and Fe+Al oxides than from Ca-P pool in high P fixing acidic soils.

Both TSP and BGPR fertilisers can increase tree needle concentration in 2 years after application even when the needle P concentrations before fertiliser application were marginally higher than the critical P concentrations, despite the soils are P deficient according to the traditional soil P tests. The reason for this is that the tree roots, probably through their association with ectomycorrhizal fungi, were able to take up P.

The weed removal at both forests increased tree growth.

Chapter 5

Synergistic and Antagonistic Effects of Broom and Ryegrass on P Nutrition of *P. radiata* Seedlings - Soil P Chemistry

5.1 Introduction

Recently, there has been a steady trend in New Zealand plantation forestry towards wider initial tree spacing and lower initial stocking of *P. radiata* (400-800 trees ha^{-1}), which has increased the potential for weed growth in forest stands as light conditions below the canopy and nutrient resources are relatively better (Gadgil *et al.*, 1988). The reasons for wider initial tree spacing are availability of better-quality nursery stock and improved establishment practices. Previously, higher stocking rates were used to help the trees grow straighter and the plantation to produce uniform trees. But now, with improved nursery stock, even without the higher initial stocking rate, the trees are uniform and grow straighter. High initial stocking rates (1200-2000 trees ha^{-1} for a final stocking rate of 200 to 350 trees ha^{-1}) are also considered to be expensive because of the costs for seedlings, planting, and thinning (MacLaren, 1993). Under wider initial spacing conditions, the response of radiata trees to P fertiliser is expected to be more influenced by the interaction between the applied P fertiliser, the tree and understorey vegetation.

Many studies have shown that competition for nutrients (antagonism) is a mechanism by which the growth rate of forest trees is reduced by understorey vegetation (Nambiar *et al.*, 1984; Smethurst and Nambiar, 1989). Therefore, intensive vegetation management practices, with heavy emphasis on herbicide use, are typical in the establishment of *P. radiata* plantations in New Zealand.

In contrast, Richardson *et al.* (1996) reported that some species of grass, herbaceous broadleaves and buddleia have significantly increased P concentrations in needles of 3-year-old radiata pine trees (synergism), but broom, gorse, lotus and pampas had no significant effect on needle P concentrations when they were grown in a moderately fertile soil in the field (Richardson *et al.*, 1993). However, the effect of these plant species on the P concentration in other parts of the tree, total P uptake by the tree from the soil or soil P changes due to these understorey species were not reported. The mechanism by which the plant species influenced the P nutrition of the tree was also not reported.

More recently, Scott (2002) reported that there was evidence of an interaction between tree and understorey on soil P dynamics. When radiata pine seedlings were grown in association with lucerne in pots, they appeared to utilize soil P to a greater extent than P utilization by ryegrass, lucerne, radiata pine grown alone or radiata pine grown with ryegrass. However, he did not report clearly the relative efficiencies of these plant species in increasing P availability.

Scott (2002) also reported that the finding of other workers, that plant-available inorganic P was increased and organic P reduced under conifers (Davis and Lang, 1991; Hawke and O'Connor, 1993; Davis, 1994; Belton *et al.*, 1995; Condron *et al.*, 1996; Chen *et al.*, 2000), was confirmed in his glasshouse study. In a field study, however, he found that P_i remained stable or declined while P_o fractions increased under conifers. He explained that this was due to an increase in soil organic carbon content and P_o in the field soil with increased time. The study site was previously managed under an arable crop/pasture rotation system. Hence, return of this land to a permanently vegetated undisturbed forestry site may have resulted in a build up of C and P_o. Scott's study was conducted on a low P-fixing soil having a high concentration of plant-available P (Olsen P 17 $\mu g\ g^{-1}$) in the South Island of New Zealand. In the North Island many of the radiata plantations are grown on P-deficient and high P-fixing soils developed on volcanic ash or pumice material (Hunter *et al.*, 1991; Hewitt, 1992). Under these conditions the interactions of radiata and understorey for P uptake may be different.

As P is an important nutrient for New Zealand forest plantations, where most soils are P deficient or marginally deficient (Hunter *et al.*, 1991), a better understanding of the soil P chemistry under radiata pine trees in association with other plants is required. This information is critical for the development of tree growth models that include a range of the understorey-associations (Richardson *et al.*, 1996) and for the efficient P fertiliser management in forest plantations.

5.2 Objectives

The objectives of the study are:

1. To investigate the effect of broom (*Cytisus scoparius* L.) and ryegrass (*Lolium multiflorum)* grown with radiata seedlings in an Allophanic Soil treated with three rates of TSP on the pH and phosphatase activity in the rhizosphere soils under glasshouse condition.
2. To study the changes in soil plant-available P and the fate of P applied in the above trial.

5.3 Materials and methods

5.3.1 Experimental design and treatments

The experiment was arranged in a split-plot design inside a glasshouse. The main-plot treatments were three rates of P fertiliser: 0, 50, and 100 mg P kg^{-1} soil (equivalent to 0, 50 and 100 kg P ha^{-1}, 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. Each main-plot was split into four split-plots consisting of four plant combinations (Figure 5.1): (1) broom alone (compartment 1), and (2) radiata with ryegrass (compartment 2) (plants in both split-plot treatments grown within the same tray, but (1) and (2) separated by a nylon mesh (43 μm opening) to stop plant roots from one compartment getting into the other); (3) ryegrass alone (compartment 1), and (4) broom with radiata (compartment 2) (grown

within the same tray, but (3) and (4) separated by a nylon mesh as carried out for plant combinations (1) and (2)). The treatments were replicated five times. This plant interference study employed the divided pots design (Chapter 2) using below-ground partitions to get the expected root interferences, meanwhile the above-ground environment for all pots was homogeneous as the order of the plants in every pot was similar (see Figure 5.1). The experiment was designed to compare the effects of below-ground interaction of radiata + ryegrass and radiata + broom on soil properties and growth and P nutrition of radiata.

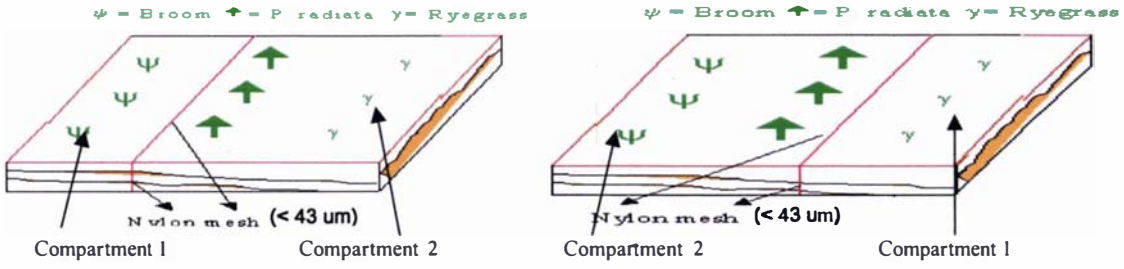

Figure 5.1 Plant combinations in trays in the glasshouse trial

Plate 5.1 The glasshouse trial layout (after 26 weeks of radiata and broom growth and after 18 weeks of ryegrass growth in an Allophanic Soil)

Plate 5.2 The glasshouse trial showing selected treatments after 26 weeks of radiata and broom growth and after 18 weeks of ryegrass growth in an Allophanic Soil

A bulk sample of soil collected from Kaweka forest, described in Chapter 3, was used in this trial. The soil was collected from a 0-10 cm depth at the centre of the square between four radiata trees after clearing the weeds. As this was a second rotation plantation where some of the topsoil had been removed during harvest of 1st rotation trees and land clearing after harvest, the FH horizon was not present in the soils. The area where the soil was collected had not received fertiliser for at least 30 years.

The soil was air-dried and passed through a 5 mm sieve to remove debris (root and foliage). A sub-sample of soil was ground to pass through a 2 mm sieve and analysed for chemical properties and P fractions. The results are shown in Tables 5.1 and 5.2.

Table 5.1 Properties of an Allophanic Soil prior to planting in a glasshouse trial *

pH (H_2O)	Olsen P $\mu g\ P\ g^{-1}$	SO_4 $\mu gP\ g^{-1}$	K	Ca	Mg	Na	CEC $cmol_c\ kg^{-1}$	Total N	Total C	P ret. %
			---------- $cmol_c\ kg^{-1}$ ---------					%		
5.7	1.4	29.3	0.29	2.9	0.58	0.12	14	0.27	5.6	92

*see section 5.4 for methods of analysis

Table 5.2 Phosphate fractions in an Allophanic Soil prior to planting in a glasshouse trial*

Resin-P	NaOH-Pi	NaOH-Po	H_2SO_4-P	Residual-P	Total
---------- mg P kg^{-1} soil ----------					
1	39	130	17	61	248

*see section 5.4 for methods of analysis

5.3.2 Planting and maintenance of trial

Rectangular plastic trays having internal dimensions of 245 mm wide, 307 mm long, and 130 mm deep were used to grow the plants. Each tray was partitioned into two compartments having 1/3 and 2/3 of tray volumes separated by a nylon mesh having 43 μm openings which was sealed with glue to the edges and bottom of the trays. The

nylon mesh was expected to stop entry of roots and most of the mycorrhizal hyphae from one compartment to the other. After 4.5 kg of air-dried soil (WC = 50%, equal to 3 kg oven-dried basis) was mixed homogeneously with the appropriate amounts of TSP, 1/3 and 2/3 of the soil weight was placed into compartments 1 and 2, respectively in the trays.

Radiata seeds obtained from Forest Research Ltd., Rotorua were germinated according to the following procedure: seeds were soaked overnight on December 10, 2001 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 22-24°C. All the seeds germinated in 7 days. When the seeds were germinated, the box containing the seedlings was transferred to the glasshouse.

A week after germination of the seeds, three radiata seedlings were transplanted into compartment 2 in each tray on 26 December 2001. At the same time, 10 broom seeds (obtained from Forest Research Ltd.) were sown directly (after soaking 5 minutes in hot water at approximately 95°C) into compartment 1 or compartment 2 depending on the treatment and a week later the seedlings were thinned to four plants per tray (Figure 5.1). Four months later (9 April 2002), ryegrass (variety Moata) seeds were sown and seven days after they germinated the seedlings were thinned to 10 plants per tray.

Five months after the planting of the radiata seedlings, a complete but –P nutrient solution (Middleton and Toxopeus, 1973) was added to all trays. The solution was prepared from the following stock solution:

- Major element A stock solution minus N and P containing 2.2 g/l of K_2SO_4, 6 g/l of $KHCO_3$.
- Major element B stock solution containing 2 g/l of $MgCl_2.6H_2O$, 0.2 g/l of $CaCO_3$, 10 ml/l of HCl, and 1.6 g/l of Na_2SO_4.
- Minor element stock solution containing 3.0 mg/l of H_3BO_3, 0.4 mg/l $CoCl_2.6H_2O$, 1.0 mg/l of $CuCl_2.2H_2O$ 20.0 mg/l of $MnCl_2.2H_2O$, 0.4 mg/l of $(NH_4)_6Mo_7O_{24}.4H_2O$ and 1.5 mg/l $ZnCl_2$.
- Nitrogen stock solution containing 26.7 g/l of NH_4NO_3.
- Ferric citrate stock solution containing 0.0585 g Fe citrate in one liter of H_2O.

A nutrient solution was made by mixing 350 ml each of Major Element solution A, Major Element B and Nitrogen stock solutions, and 35 ml of Minor Element stock solution and 20 ml of Fe citrate stock solution. The solution was diluted to 7500 ml with distilled water. The nutrient solution was applied at a rate of 450 ml per tray 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 three-four day interval. In total, each tray received 54.2 mg N/kg soil and 35 mg K/kg soil (equivalent to 54 kg N/ha and 35 kg K/ha, respectively).

The glasshouse was maintained at 28°C maximum and 13°C minimum temperatures. Soil water content was maintained at 80% field capacity by bringing the weight of tray and soil to the required weight by adding distilled water (field capacity of Kaweka forest soil was 87% gravimetric moisture content). The weight of soil in each tray at 80% field capacity was 5.1 kg. Water was added to the trays daily during summer months and once every two to three days during winter. The ryegrass was harvested on 20 September 2002 (22 weeks after planting) and again on 21 February 2003 (42 weeks after planting). The broom and radiata were harvested on 24 February 2003 (56 weeks after planting).

5.3.3 Measuring plant-available P in soils *in situ* with resin membrane

Cation and anion exchange resin membranes (cation – CER, anion – AER) were used to determine labile ammonium, nitrate and phosphate in soils *in situ* at 54 weeks (2 weeks prior to plant harvest) after TSP application to the soil in the trays.

The ion exchange membranes used were manufactured from synthetic resins and supplied by BDH Chemicals Ltd., England. The area of the membrane strips was 31.25 cm^2 (6.25 cm long and 2.50 cm wide).

The following experiments were carried out on the resin strips before using them in the glasshouse trial.

Experiment 1: The ability of KCl saturated resin membranes to extract phosphate, ammonium, and nitrate from soil

The study was conducted inside a laboratory to measure the amount of P and N (NO_3^--N and NH_4^+-N) extracted by resin membrane strips (5 cm^2) from Kaweka forest soil (0-10 cm depth) (chemical properties and P fractions of the soil described in section 5.3.1). This technique was recently used by Saman (2003) to extract NH_4^+ and NO_3^- from pasture soils.

Soils were air-dried and passed through a 5 mm sieve. Samples of this soil weighing 120 g (equivalent to 100 g oven-dried soil moisture content 20%) were weighed in plastic containers. The soils were treated with P fertiliser at the rate of 0 and 48.4 mg TSP/100 g soil (equivalent to 0 and 100 kg P ha^{-1} using bulk density of 1 g cc^{-1} and soil depth 10 cm). These rates were the same as those tested in the glasshouse trial. Cation and anion resin membranes were saturated with K^+ and Cl^- respectively using 3 M KCl. The resin membranes were buried in the soil in vertical slits opened with a hand trowel. The slits were then closed by firmly pressing the soils on both sides of the spikes to ensure uniform membrane-soil contact. Each container had one anion and one cation resin membrane. Each treatment had three replicates. The soil medium was kept at 80% field moisture capacity by adding deionized water. The strips were removed after 3, 6, and 15 days of incubation time and eluted by shaking for 1 h with 20 ml 2 M KCl and N ($NO3^-$ and NH_4^+) and the P concentration was determined by a Technicon Autoanalyzer (Searle, 1975) and the Murphy and Riley (1962) method, respectively. The results are shown in Table 5.3.

After the N and P analysis, all cation exchange membranes (CEM) were re-saturated with K^+ and anion exchange membranes (AEM) with Cl^-, by placing them into (1 litre) plastic bottles containing 100 ml of 3 M KCl and shaking them for 30 minutes. The solution was then discarded, and refilled with a fresh solution of KCl and the resin strips were shaken as before to completely saturate them with K^+ (for CEM) and Cl^- (for AEM). All spikes were then thoroughly washed three times with deionised water and kept in deionised water for reuse.

Table 5.3 Resin-extractable N (NO_3^--N and NH_4^+-N) and P after 3, 6, and 15 days of incubation time in an Allophanic Soil in a laboratory

Treatment				
P fert. rate (kg/ha)	Incubation time (days)	NO_3^--N	NH_4^+-N	P
		----- (μeq-N/5 cm^2) -----		(μeq-P/5 cm^2)
0	3	18.0	<0.36**	0.013
		17.5	<0.36	0.013
		16.7	<0.36	0.006
	Average	17.4 ± 0.4*	<0.36	0.011 ± 0.002
	CV (%)	3.7	-	34.6
0	6	31.4	<0.36	0.013
		34.3	<0.36	0.013
		31.1	<0.36	0.013
	Average	32.3 ± 0.4	<0.36	0.013 ± 0**
	CV (%)	5.5	-	0
0	15	56.6	<0.36	0.006
		65.2	<0.36	0.006
		58.7	<0.36	0.006
	Average	60.2 ± 2.6	<0.36	0.006 ± 0
	CV (%)	5.5	-	0
100	3	17.0	<0.36	0.006
		21.6	<0.36	0.006
		19.3	<0.36	0.006
	Average	19.3 ± 1.3	<0.36	0.006 ± 0
	CV (%)	11.9	-	0
100	6	34.5	<0.36	0.006
		31.0	<0.36	0.006
		29.2	<0.36	0.013
	Average	31.6 ± 1.6	<0.36	0.009 ± 0.02
	CV (%)	11.9	-	43.3
100	15	46.7	<0.36	0.006
		60.4	<0.36	0.006
		44.1	<0.36	0.006
	Average	50.4 ± 5.1	<0.36	0.006 ± 0
	CV (%)	11.9	-	0

* Standard error of means

** Detection limit

The results show that NO_3^--N extracted from the soil by resin membrane pre-saturated with Cl^- had a low variation between the replicates. The increase of NO_3^--N concentration extracted by the resin membranes over time at the two P rates was probably due to mineralisation of organic matter and the subsequent nitrification of ammonium. The resin membranes, however, failed to extract significant amounts of NH_4^+-N and P at both rates of P addition. However, Saman (2003) was able to extract significant amounts of NH_4^+ from pasture soils (Manawatu sandy loam) using K^+-saturated resin membrane and the amounts of NH_4^+ extracted were highly correlated with those extracted by 2 M KCl. In the present study KCl extractable NH_4^+ would have given some clue to this but this analysis was not carried out on the samples. The insignificant amounts of NH_4^+ extracted by the resin in the present study could be due to very low levels of NH_4^+ in this Allophanic soil, which was taken from the forest compared with the pasture soil of Saman's (2003) which is commonly rich in NH_4^+. Another reason for the low resin extractable NH_4^+ could be due to the strong retention of K^+ on the resin membrane surface compared to NH_4^+ as observed by Saman (2003), hence it was difficult for the small amounts of NH_4^+-N in the Allophanic Soil to be exchanged by K^+ on the resin membrane.

Table 5.3 also shows that P extracted by Cl^- saturated resin was very low and it did not increase as a result of P addition to the soil at the rate of 100 kg P ha^{-1}. This may be because Cl^- on the resin membrane surface may not be strong enough to extract P from this high P-fixing soil. Bache and Ireland (1980) also reported that P extracted by the Cl^--resin was lower than that by HCO_3^--resin. They explained that the reasons why HCO_3^--resin extracted more P from soil than Cl^--resin was possibly due to more efficient direct desorption of $H_2PO_4^-$ by HCO_3^- and by the higher OH^- concentration produced by the hydrolysis of HCO_3^-. Tran *et al.* (1992) who studied the amount of P extracted by resin saturated with different anions, reported that P extracted from soil increased in the following order: Cl^-, HCO_3^-, F^-, and H-OH.

Experiment 2: Effect of the type of anion saturating the resin membrane on P extraction from the solution

Because Cl^- saturated resin was not able to extract P from soil, the anion strips (6.25 cm long and 2.50 cm wide = 31.25 cm^2) were saturated with HCO_3^- and its ability to extract P from the solution was compared with that of Cl^- saturated resin membrane. Bicarbonate anion was selected for saturating the resin strip because this anion is a component of the extractant used in the Olsen soil P test, which extracts a significant amount of P in soils (Olsen *et al.*, 1954; Blackmore *et al.*, 1987) and also because Sibbesen (1978), Tran *et al.* (1992) and Turrion *et al.* (1999) reported that HCO_3^--saturated resin extracted P better than Cl^--saturated resin did in soils with a range of P status. The P extraction was performed initially in this experiment in solution as this is a simpler system than the soil system. Anion resin membranes (after being pre-saturated with HCO_3^- or Cl^- in 0.5 M $NaHCO_3$ and 3 M KCl, respectively) were immersed overnight in a 50 ml KH_2PO_4 solution containing 6200, 62000, 124000, and 248000 µg P. The following day, the membranes were eluted by shaking for one hour with 20 ml 0.5 M NaCl and P analysed by the Murphy and Riley method (1962). The results are shown in Figure 5.2.

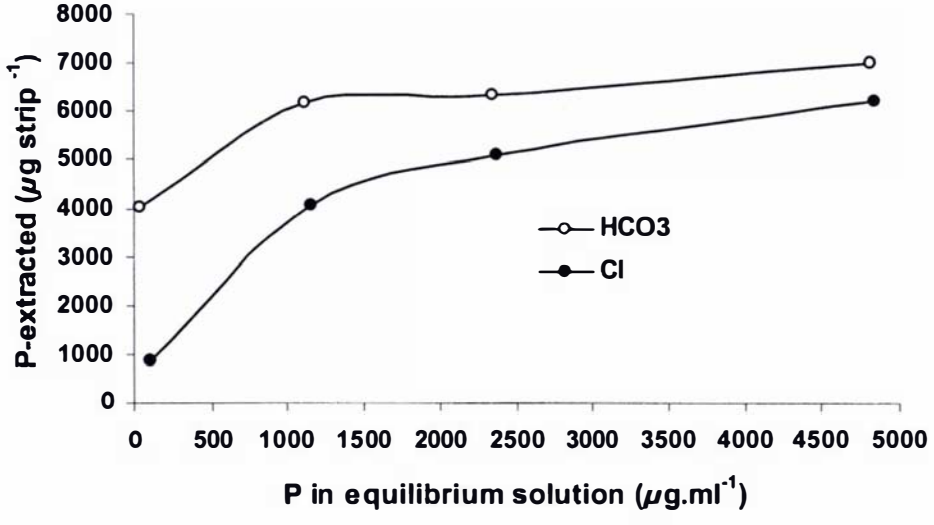

Figure 5.2 P-extracted from KH_2PO_4 by anion resin membranes saturated with Cl^- and HCO_3^- after 24 hours in a laboratory

The results show that HCO_3^- is more efficient than Cl^- in exchanging with $H_2PO_4^-$ in solution and this effect is more striking at low P concentrations in the solution. The reason for this is not clear but may be due to the slightly higher pH in the HCO_3^- resin system leading to slightly more HPO_4^{2-} species which would have had higher affinity to the resin.

Experiment 3: Exchange capacity of anion resin membrane

This experiment was set up to measure the exchange capacity of anion resin membranes (6.25 cm x 2.5 cm = 31.25 cm^2) by determining the maximum amount of P the membrane can adsorb and to determine the number of elutions required to leach all the P that was adsorbed to the resin membranes. Anion resin membranes (after being presaturated with HCO_3^- using 0.5 M $NaHCO_3$) were immersed overnight in a 50 ml KH_2PO_4 solution containing 6200, 62000, and 124000 µg P/50 ml, respectively). The following day, the membranes were removed from the solution, rinsed with water and the P adsorbed was eluted by shaking for one hour with 20 ml 0.5 M NaCl. The results are presented in Figure 5.3.

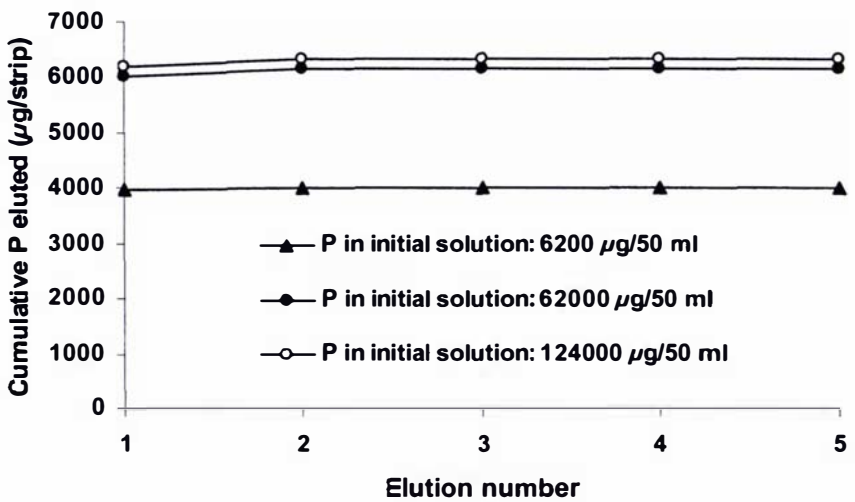

Figure 5.3 Cumulative P eluted after shaking P-saturated resin membranes number of times with NaCl in a laboratory

The results showed that one elution is sufficient to remove all P adsorbed to the resin and a maximum of 6200-6300 μg P was adsorbed from an external solution containing 1.24 x 10^5 μg P/50 ml. Hence, the anion exchange capacity of the resin strip was calculated to be 200 - 204 μeq/strip which is approximately the same as the 200 – 210 μeq/strip reported by Saggar *et al.* (1990) for P adsorption (this assumes sorption as $H_2PO_4^-$).

Experiment 4: Evaluating the use of HCO_3^--saturated anion resin membrane for extracting P and NO_3^- and Na^+-saturated cation resin membrane for extracting NH_4^+ from soils

Experiment 1 showed that the K^+-saturated cation resin membrane was not able to extract significant amounts of NH_4^+-N from soils. The present experiment was conducted to determine whether the cation exchange resin membranes which were pre-saturated with Na^+ from 0.5 M NaCl can extract NH_4^+ and the anion exchange resin membranes which were pre-saturated with HCO_3^- from 0.5 M $NaHCO_3$ can extract NO_3^- and P from Kaweka soil (0-10 cm depth). Another objective of the experiment was to compare P extracted by resin membranes with the Bray-2 P test on the same soils.

The soils were air-dried and passed through a 5 mm sieve and placed in pots. Each pot contained 115 g air-dried soil (equivalent to 100 g oven-dried soil; moisture content 15%). The soils were treated with TSP fertiliser at rates of 0 and 48.4 mg TSP 100 g^{-1} (equivalent to 0 and 100 kg P ha^{-1}). Each pot had one AER strip and one CER strip. Nylon fishing line (20 cm length) was sewn onto the strips to attach labels and for easy removal of the membranes from the soil at the end of the experiment. The resin membranes were buried in the soil by opening a vertical slit with a hand trowel. Then the slit was closed by firmly pressing the soils at both sides of the membrane to ensure uniform membrane-soil contact. Each treatment had nine replicates (nine pots). The soil was adjusted to 80% field moisture capacity (gravimetric) by adding deionised water (FC of Kaweka Forest soil = 87% moisture content). Resin membranes were removed from the soil after 3 days of incubation time and soil samples were taken from the same slit for Bray-2 P analysis. The ions adsorbed to the strips were eluted by shaking for 1

h with 20 ml of 0.5 M NaCl and N (NO_3^- and NH_4^+) and P concentrations were measured as before. The results are presented in Table 5.4 and 5.5.

Table 5.4 Ammonium extracted by Na^+-saturated resin and NO_3^- extracted by HCO_3^--saturated resin after 3 days of incubation time in an Allophanic Soil in a laboratory

No	P fert. rate (kg P/ha)	μeq NH_4^+-N/strip	μeq NO_3^--N/strip
1.	0	5.4	74.0
2.		7.6	56.4
3.		6.0	57.1
4.		7.3	82.7
5.		7.6	67.7
6.		3.3	73.0
7.		5.4	46.1
8.		5.8	59.3
9.		4.8	80.4
		Average 5.9 ± 0.5*	66.3 ± 4.0
		CV (%) 25.4	18.1
10.	100	6.7	86.3
11.		4.4	38.6
12.		5.5	58.4
13.		6.9	62.9
14.		7.4	44.0
15.		9.3	73.4
16.		4.2	74.9
17.		6.8	76.6
18.		5.8	46.0
		Average 6.3 ± 0.4	65.4 ± 5.6
		CV (%) 19.0	25.2

* Standard error of means

The results show that resin membranes (presaturated with HCO_3^- from 0.5 M $NaHCO_3$ for the AER strips and Na^+ from 0.5 M NaCl for the CER strips) extracted significant

amounts of N (both NO_3^- and NH_4^+) and P from Kaweka Soil (Allophanic Soil) and the variations among the replicates were low (Table 5.4 and 5.5). The increased quantities of NH_4^+-N extracted by Na^+-saturated resin membrane compared to no NH_4^+-N extracted by K^+-saturated resin membrane in Experiment 1 now provide evidence that K^+ is preferentially adsorbed to resin strips as suggested by Saman (2003).

There was a significant increase in P extracted by resin when P fertiliser was applied, as observed for Bray-2 P (Table 5.5). This shows that HCO_3^--saturated resin membrane extractable P responds to changes in P availability in soil unlike Cl^--saturated resin membrane extractable P in Experiment 1. As there was no N addition to the soils, there was no difference in the amount of N (NO_3^- and NH_4^+) extracted between the two P rates of addition (0 kg P ha^{-1} and 100 kg P ha^{-1}).

The P extracted by the HCO_3^--saturated anion exchange resin membrane and Bray-2 P can not be compared as the two are expressed by different units. This is also due to the difference in the mechanism of P extraction in the two methods. The resin membrane extracted P by an anion exchange mechanism whereas the Bray-2 P test is based on a chemical reaction between soil and extractant. In addition, in the resin method, P desorption from soil to soil solution is a rate-determining step (Sibbesen, 1978) before the P diffuses and adsorbs to the resin membrane. There was a higher variation between replicates for resin membrane extractable P than for Bray-2 P concentration. This is due to differences in contact between the resin strip and the soil among the replicates and soil moisture and porosity differences in the vicinity of the resin membranes, which causes differences in the rate of P diffusion to the resin membrane surface.

Table 5.5 P extracted by HCO_3^--saturated resin strip and Bray-2 P after 3 days of incubation time in an Allophanic Soil in a laboratory

No.	P fert. rate (kg P/ha)	Resin-P_i 1st elution	Resin-P_i 2nd elution	Resin-P_i Total 1st + 2nd	Bray-2 P (μg P/g soil)
		---------- (μg P/strip) ----------			
1.	0	0.2	0.0	0.2	2.7
2.		0.4	0.0	0.4	2.7
3.		0.2	0.0	0.2	2.5
4.		0.2	0.0	0.2	2.6
5.		0.2	0.0	0.2	2.7
6.		0.2	0.0	0.2	
7.		0.2	0.0	0.2	
8.		0.2	0.0	0.2	
9.		0.2	0.0	0.2	
		Average		0.2 ± 0.0*	2.6 ± 0.0
		CV (%)		30	4.5
10.	100	6.2	0.2	6.4	18.4
11.		5.4	0.0	5.4	17.1
12.		7.6	0.4	8.0	20.2
13.		8.8	0.2	9.0	18.3
14.		4.2	0.0	4.2	18.6
15.		8.0	0.2	8.2	
16.		5.8	0.0	5.8	
17.		6.2	0.0	6.2	
18.		4.8	0.2	5.0	
		Average		6.5 ± 0.5	18.5 ± 0.5
		CV (%)		25.9	7.9

*Standard error of means

Experiment 5: Effect of contact time between soil and resin membrane on P extracted from soil

The experiments discussed until now were conducted on soils treated with TSP in the laboratory for short periods of time. Experiment 5 uses soils from a field trial (Chapter

3) where TSP was applied to soils two years before the soils were sampled for this study. The results were expected to give information on the ability of the resin membranes to extract P under field conditions. The experiment was also designed to determine the length of time the resin strip should be left in the soil before removal for P determinations.

Soils were collected at 0-10 cm depth from the field trial (sited at Kaweka forest) from plots treated with 0, 100, and 200 kg P ha^{-1} as TSP. Soils from 3 replicates of these treatments were collected. Soils were air-dried and passed through a 5 mm sieve and placed in pots. Each pot contained 6.56 kg soil (moisture content 64%) (4 kg oven dried soil). The soils were kept moist at 80% field moisture capacity (gravimetric) by adding deionized water (FC of Kaweka Forest soil = 87% gravimetric moisture content) for 15 days.

Only AER strips saturated with HCO_3^- were used to extract P in this experiment. Two days after establishing the soil at 80% field capacity, five AER strips were inserted vertically into the soil in each pot, as described previously. The resin strips were removed from the soil 2, 4, 6, 10, and 15 days later and P retained on the strips was eluted by a 0.5 M NaCl solution and the P concentration in the eluted solution was measured as before. Bray-2 P concentrations were also determined on soils removed from the slits. The results are presented in Figures 5.4 and 5.5.

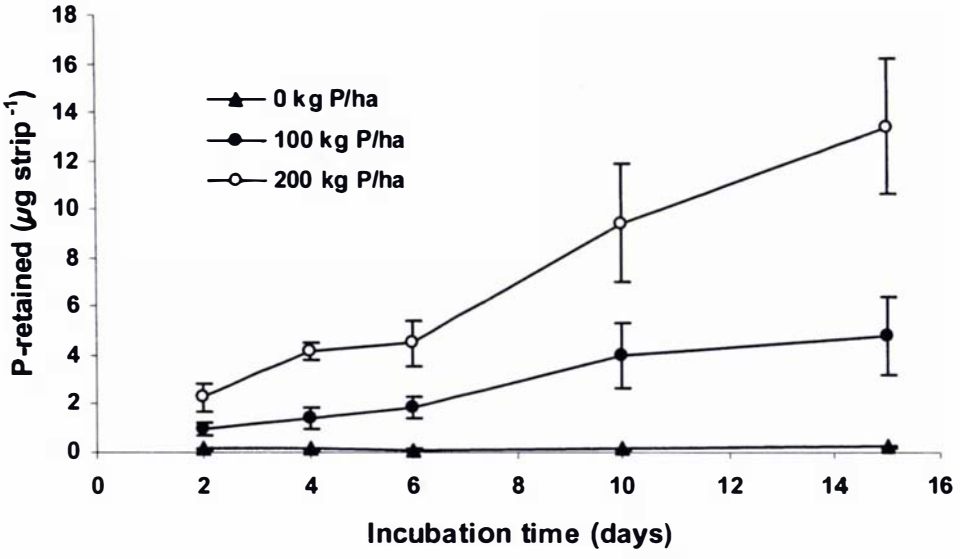

Figure 5.4 P retained on HCO_3^--saturated resin strips after different times of contact with an Allophanic Soil treated with TSP at three rates (vertical bars are standard error of means) in a laboratory

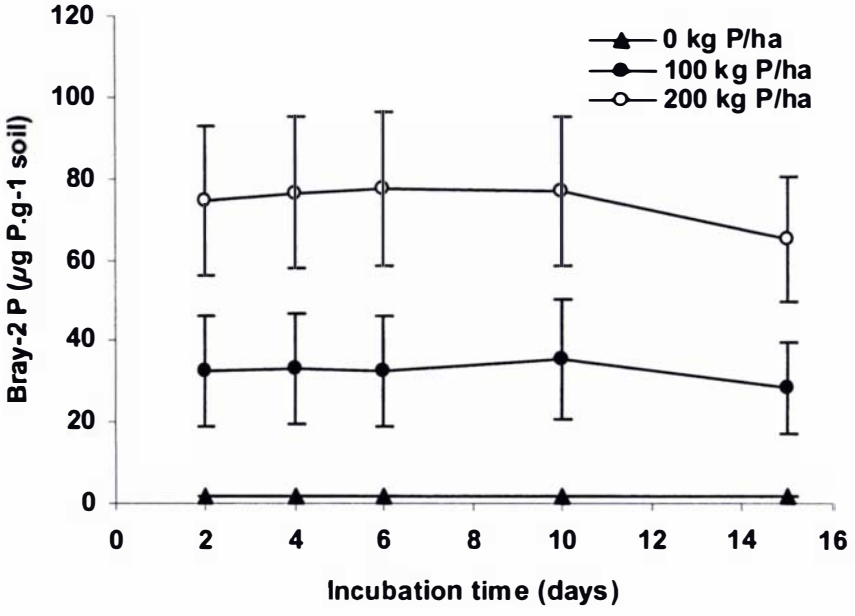

Figure 5.5 Bray-2 P after different times of incubation in an Allophanic Soil treated with TSP at three rates (vertical bars are standard error of means) in a laboratory

The results showed that HCO_3^--saturated resin extractable P significantly increased with increasing rates of P that had been applied to field soils 2 years before these measurements were made. There were also similar increases in Bray-2 P concentrations. This shows that P extracted by HCO_3^--saturated resin strips responded well to increased P availability in field soils and this is a useful technique for measuring soil P availability *in situ*.

A striking difference between Bray-2 P and resin-P_i concentrations is that the former did not change with incubation time whereas the resin-P concentration increased with the increase in incubation time. This is, probably, because in Bray-2 P extraction equilibrium is reached between the extractant and soil P in one minute of shaking time whereas in resin-P extraction, the amount of P adsorbed to the resin strip is diffusion controlled. Phosphorus diffusion to the resin strip continues with time causing an increase in P absorption on the resin strip. The diffusion rate is expected to increase with increased P concentration in the bulk soil and this may be the reason for the increased rate of P retention with time at an incubation time of $\geq$ six days. The increase in resin-P_i with time is likely to be also due to the slow release of P by desorption from soil, as observed by Bache and Ireland (1980).

As resin-P_i concentration increases more markedly from six days of incubation onwards, it was decided to leave the resin strips in contact with the soil for six days before P measurements are made in the glasshouse experiment. As there are markedly significant differences in resin-P_i concentration from four days onwards leaving the resin strips for six days is expected to show differences between treatments in the glasshouse experiment.

5.3.4 Plant sampling

Ryegrass was harvested twice during the experiment – firstly, 22 weeks (20 September 2002) after ryegrass seeds were sown and, secondly, at the end of the experiment at 42 weeks (21 February 2003) after ryegrass seeds were sown. Broom and radiata were

harvested only at the end of the experiment at 54 weeks (22 February 2003) after planting these seedlings. Shoot biomass for all plant species was collected by cutting 1 cm above the soil surface. The roots were washed after collecting the bulk and rhizosphere soils from each plant (see next section). Roots and shoots were dried at 70°C to constant weight. After recording their weights, they were ground using a hand-held Breve coffee grinder.

5.3.5 Soil sampling

The root-soil mass was shaken gently and the fallen soil mass was collected. This represented the bulk soil (bk). The soil adhering to the roots after the bulk soil had fallen away was collected by aggressively shaking the roots (Adamo *et al.*, 1995; Wang and Zabowski, 1998). This soil represented the rhizosphere (rh) soil. Each main-plot treatment (P fertiliser rates) had four bulk soils and six rhizosphere soils, which are referred to as (see Figure 5.1):

- bulk soil from broom alone - compartment 1 (B_1-bk)
- rhizosphere soil from broom alone - compartment 1 (B_1-rh)
- bulk soil from radiata grown with grass - compartment 2 (R_2+G_2-bk)
- rhizosphere soil from radiata grown with grass - compartment 2 (GR_2-rh)
- rhizosphere soil from grass grown with radiata - compartment 2 (RG_2-rh)
- bulk soil from broom grown with radiata - compartment 2 (B_2+R_2-bk)
- rhizosphere soil from broom grown with radiata - compartment 2 (RB_2-rh)
- rhizosphere soil from radiata grown with broom - compartment 2 (BR_2-rh)
- bulk soil from grass alone - compartment 1 (G_1-bk)
- rhizosphere soil from grass alone - compartment 1 (G_1- rh).

All soil samples were passed through a 2 mm sieve to remove debris (obvious root and foliage) and stored at 4°C. The following day, the acid phosphatase activity in the soil samples was measured. The remaining soil samples were air dried and stored for measuring pH, Bray-2 P and P fractions.

5.3.6 Chemical analysis

Soil pH

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°C after which pH was determined using a pH meter equipped with a glass electrode (Blakemore *et al.*, 1987).

Bray-2 P

Bray-2 P was determined by shaking for one minute 2.5 g of air dry soil in 25 ml of a solution containing ammonium fluoride (0.3 M NH_4F) and hydrochloric acid (0.1 M HCl) (Blackmore *et al.*, 1987). The suspension was filtered and P was analysed by the colorimetric technique of Murphy and Riley (1962).

P retained by resin membrane (*in situ *measurement)

The resin strips (after removal from the soil) were eluted by shaking for 1 h with 20 ml 0.5 M NaCl. The concentrations of P extracted were measured by the colorimetric technique of Murphy and Riley (1962).

NO_3-N and NH_4-N retained by resin membrane (*in situ *measurement)

The resin strips (after removal from the soil) were eluted by shaking for 1 h with 20 ml 0.5 M NaCl. The concentrations of NO_3^--N and NH_4^+-N extracted were measured by a Technicon auto-analyser (Searle, 1975).

Soil P fractions

Soil P fractions were measured by the P fractionation procedure of Hedley *et al.* (1994). A 1 g soil sample was placed into a 50 ml polypropylene centrifuge tube and the following P fractions were sequentially analysed.

(1) Resin-P_i: by shaking end-over-end for 16 hours at 25°C in 30 ml of deionised water containing a Na^+-saturated cation exchange resin membrane strip and a HCO_3^--saturated anion exchange resin membrane strip. At the end of the shaking, the strips were transferred into 50 ml centrifuge tubes using tweezers and the P retained on the

resin strips was eluted by shaking end-over-end for 30 minutes with 20 ml of 0.5 M NaCl.

(2) 0.1 M NaOH-P_i: 3.3 ml of 1 M NaOH was added to the suspension from step (1) to make the final concentration of the NaOH solution in the suspension 0.1 M. The tubes with the contents were shaken for a further 16 hours. Samples were then centrifuged at 8000 rpm for 10 minutes and the supernatant filtered through a 0.45 μm Millipore filter.

(3) 0.1 M NaOH-P_o: 5 ml of the 0.1 M NaOH extractant from (2) was digested with 4 ml of concentrated H_2SO_4 (95-97%) and 1 ml of H_2O_2 (30%). NaOH-P_o concentration was calculated by subtracting 0.1 M NaOH-P_i concentration in (2) from the concentration of P in the digest.

(4) H_2SO_4-P_i: 30 ml of 0.5 M H_2SO_4 was added to the soil residue from step (3) and the contents were shaken for 16 hours, centrifuged and filtered.

(5) Residual-P: The soil residue from step (4) was digested in 8 ml of concentrated H_2SO_4 (95-97%) at 350°C for 3 h, cooled, added 0.5 ml H_2SO_4 and reheated until the residue was white. The digests were then made up to 50 ml with deionised water and filtered through a 0.45 μm Millipore filter. To avoid the precipitation of Fe- hydroxide and to minimise the use of NaOH in neutralisation, only a 5 ml aliquot was transferred into a 50 ml flask and neutralized with 5 M NaOH using a *p*-nitrophenol indicator, before the P was analysed.

The P concentrations of all the above extracts and digests were measured by the colorimetric technique of Murphy and Riley (1962).

5.3.7 Acid phosphatase enzyme activity

Only acid phosphatase enzyme activity was measured in this study because the soil used in the trial was acidic (pH = 5.7), and acid phosphatase is expected to be the dominant phosphatase enzyme (Eivazi and Tabatabai, 1977). Acid phosphatase activity was measured according to the method described by Tabatabai (1994). Moist soils (1 g oven-dried weight equivalent, < 2 mm) were incubated with a 0.20 ml toluene and a 1 ml *p*-nitrophenyl phosphate solution (*p*-nitrophenyl phosphate, disodium hexahydrate) in a 4 ml modified universal buffer (MUB) solution of pH 6.5 at 37°C for 1 h. The MUB was made by mixing 12.1 g of tris (hydroxymethyl) aminomethane (THAM), 11.6 g of maleic acid, 14.0 g of citric acid, and 6.3 g of boric acid (H_3BO_3) in 488 ml of 1 M sodium hydroxide (NaOH) and diluting the solution to 1 L with water. The amount of *p*-nitrophenol released after one hour was measured on a UV spectrophotometer at 412 nm and the enzyme activity was expressed as μg *p*-nitrophenol released per g of dry-soil per hour.

5.3.8 Statistical analysis

An analysis of variance (ANOVA) for a split-plot design was performed using SAS (SAS Institute, 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). Resin P fraction data and resin P *in situ* measurement data were square root transformed because the spread was proportional to the square root of the mean. H_2SO_4-P_i fraction data, and Bray-2 P data were $\log_e$ transformed because the spread was proportional to the treatment mean (Anon, 2000; Steel *et al.*, 1997).

5.4 Results and discussion

5.4.1 Soil pH

The rates of P fertiliser application had no effect on soil pH, but significant differences (p<0.0001) in soil pH were observed between plant combinations (Table 5.6; Figure 5.6). The interactive effect of the P rate and plant combinations on soil pH was also significant (p< 0.0001).

Table 5.6 Effect of TSP fertiliser rate and plant combinations on pH in bulk and rhizosphere soil after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

Sampling position	P rate (μg P.g^{-1} soil)		
	0	50	100
B_1-bk	5.76 a*	5.77 ab	5.67 bc
B_1-rh	5.74 a	5.70 bc	5.57 c
R_2+G_2-bk	5.59 bc	5.79 ab	5.77 a
GR_2-rh	5.61 bc	5.17 e	5.30 d
RG_2-rh	5.68 ab	5.57 d	5.61 bc
R_2+B_2-bk	5.73 ab	5.88 a	5.80 a
RB_2-rh	5.72 ab	5.59 cd	5.60 c
BR_2-rh	5.50 c	5.17 e	5.29 d
G_1-bk	5.69 ab	5.77 ab	5.80 a
G_1-rh	5.66 ab	5.75 b	5.73 ab
$lsd_{(p<0.05)} = 0.13$ *(plant combination)*			

*Numbers under each P rate followed by the same letters are not different at P<0.05

The effect of interaction between the P rate and plant combinations on soil pH is explained below. The pHs of radiata rhizosphere soils either grown with broom or grass were significantly (p<0.05) lower than those in the bulk soils and the bulk and rhizosphere soils of grass and broom whether they were grown alone or grown with radiata for the additions of 50 and 100 μg P g^{-1} soil. However, such differences did not

occur for the control treatment (0 μg P g^{-1} soil). The lower pH under radiata is due to predominantly NH_4^+ rather than NO_3^- uptake by radiata plants (Olykan and Adams, 1995), which results in excess cation over anion uptake causing H^+ release by roots to maintain electroneutrality within plant cells (Gijman, 1990ab; Haynes, 1990; Hinsinger and Gilkes, 1995). The acidification in the radiata rhizosphere could also be due to oxalate anion released by radiata roots (Malajczuk and Cromack, 1982) with an associated H^+ release. The reason for radiata rhizosphere soil in treatments receiving 0 μg P g^{-1} soil not having any significant reduction in pH is that the root growth (see Chapter 6) and mycorrhizal hyphae development at this P rate were too low to release sufficient H^+ by root and hyphae to cause significant pH reduction in the rhizosphere.

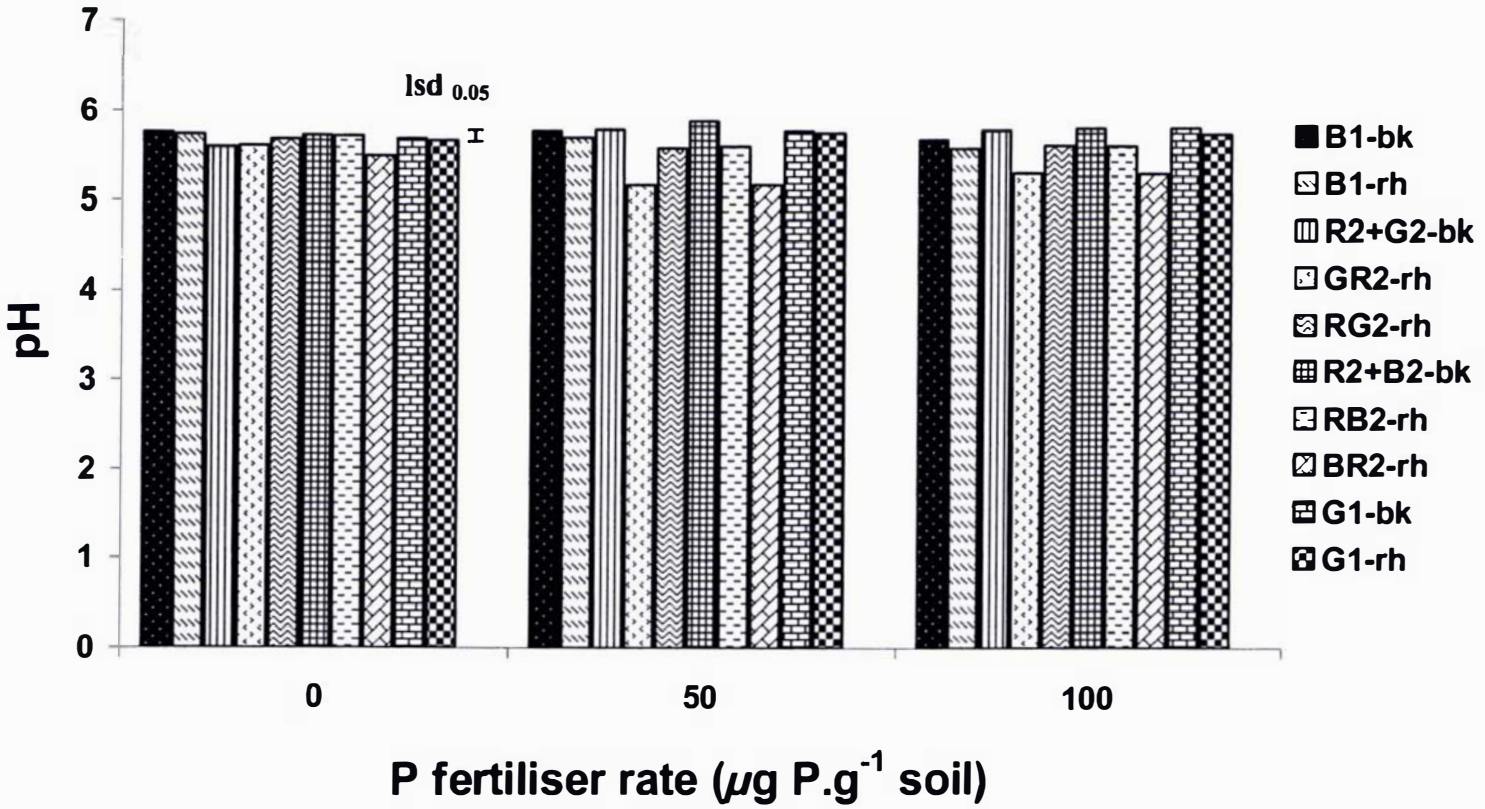

Figure 5.6 Effect of TSP the fertiliser rate and plant combinations on soil pH (1 : 2.5 w/w soil to water ratio) after 54 weeks of plant growth in an Allophanic Soil in a glasshouse ($lsd_{(p<0.05)} = 0.13$ *(for plant combinations)*

No significant pH difference was observed between grass or broom rhizosphere soils and the associated bulk soils in the absence of radiata (G_1-rh vs G_1-bk and B_1-rh vs B_1-bk), suggesting that these two plants do not have the same mechanism of ion uptake or organic anion excretion as radiata. In contrast to radiata, grass has been shown to take up predominantly NO_3^- rather than NH_4^+ (Gahoonia *et al.*, 1992a). Broom, being a legume, was expected to export H^+ into the rhizosphere when actively fixing N_2, thus causing the acidification of rhizosphere soils (Nyatsanga and Pierre, 1973; Bolan *et al.*, 1991). But such rhizosphere acidification under broom was not observed in this study.

Davis (1995) reported that the soil pH increased slightly under grass and decreased slightly under pines one year after growth of these plants in a glasshouse trial. Scott (2002) also reported that in a soil which was low in total P and carbon content, soil pH decreased significantly under pines compared with soil pH under grass and the legume lucerne in a glasshouse trial. The pH under lucerne was lower than that under grass.

At the highest P rate (100 μg P g^{-1} soil) the pH in rhizosphere and bulk soils of broom grown alone (B_1-rh, B_1-bk) were significantly lower than that in the rhizosphere and bulk soils of grass grown alone (G_1-rh, G_1-bk). This may be because at high P rates the NO_3^- uptake by grass would have been higher resulting in higher alkalinity production in the soil. At this P rate, broom would have fixed higher amounts of atmospheric N, producing higher acidity in the soil.

For the 50 and 100 μg P g^{-1} soil treatments, the soil pH was significantly lower in the grass rhizosphere soil compared to the bulk soil when grass was in association with radiata (RG_2-rh vs R_2+G_2-bk) and the broom rhizosphere soil compared to the bulk soil when broom was in association with radiata (RB_2-rh vs R_2+B_2-bk). This is probably due to the effect of radiata, because in the absence of radiata (compartment 1) there was no significant difference in pH between rhizosphere and bulk soils for both grass and broom. When broom and grass were present with radiata (compartment 2) there was an intermingling of the roots of these plants with those of radiata and, hence, the rhizosphere of radiata influenced those of the two associated plants. Scott (2002) also

observed that the soil pH under ryegrass or broom in association with radiata was significantly lower than that when they were grown alone in a glasshouse trial.

5.4.2 Phosphatase activity

The main effects of P fertiliser rates (p=0.0012) and plant combinations (p<0.0001) on acid phosphatase activity in soils were significant. But the P fertiliser rate x plant combination interaction was not significant.

The acid phosphatase activity decreased with an increased rate of P application (Figure 5.7). This is probably because the acid phosphatase enzyme is an adaptive enzyme whose activity increases when there is a need for it to function, that is, when the soils are P deficient (Haußling and Marschner, 1989). These results are consistent with those of Pang and Kolenko (1986) who found that addition of 20 μmol orthosphosphate to 1 g soil sampled from a 34-yr-old Douglas-fir forest reduced phosphatase activity in the soil. Fox and Comerford (1992a) also reported that the application of KH_2PO_4, at the rate of 6.7 and 13.3 mg P kg^{-1} soil as KH_2PO_4, decreased phosphatase activity in rhizosphere soils collected from slash pine plantations.

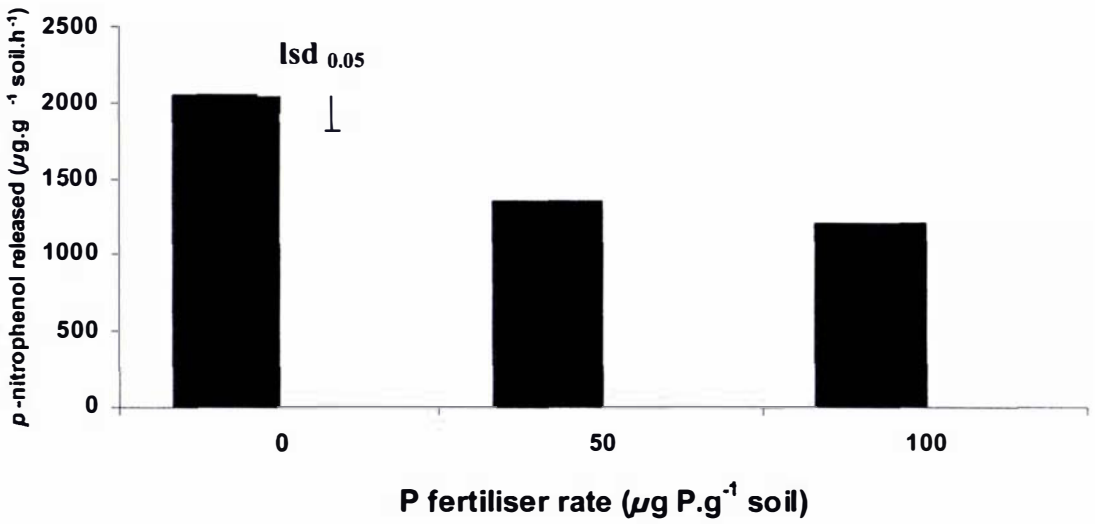

Figure 5.7 Effect of TSP fertiliser rates on acid phosphatase activity in soil (mean of plant combinations, and rhizosphere and bulk soils) after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

In general, the acid phosphatase activity in all rhizosphere soils was consistently higher than that in the bulk soils, but the differences were significant ($p<0.05$) only between the bulk soils and rhizosphere soils of radiata and broom when they were in association with each other (BR_2-rh and RB_2-rh vs R_2+B_2-bk) (Figure 5.8). The higher activity of this enzyme in the rhizosphere is due to the influence of plant roots and higher soil microbial activity in the rhizosphere than in the bulk soil (Dinkelaker and Marschner, 1992). Others have also reported that the soil in the rhizosphere of plants had higher phosphatase activity than that in the bulk soils (Hedley *et al.*, 1982a; Tarafdar and Junk, 1987; Hauβling and Marschner, 1989; Jungk *et al.*, 1993; Asmar *et al.*, 1995; Chen *et al.*, 2002; Scott, 2002). The differences in phosphatase activity between rhizosphere soils and bulk soils were lower for broom and grass when they were grown without radiata (compartment 1) than when they were grown with radiata (compartment 2). The higher differences in phosphatase activity between broom and grass rhizosphere and the corresponding bulk soils in the presence of radiata are probably due to the higher phosphatase enzyme production by the ectomychorrizal radiata roots (Skinner and Bowen, 1974; Hauβling and Marschner, 1989; Antibus *et al.*, 1992; Scott, 2002), which were intermingled with broom or grass roots in compartment 2. Due to this intermingling of roots the enzyme activity did not differ between the rhizosphere soils of radiata and the associated plants (GR_2-rh vs RG_2-rh and BR_2-rh vs RB_2-rh).

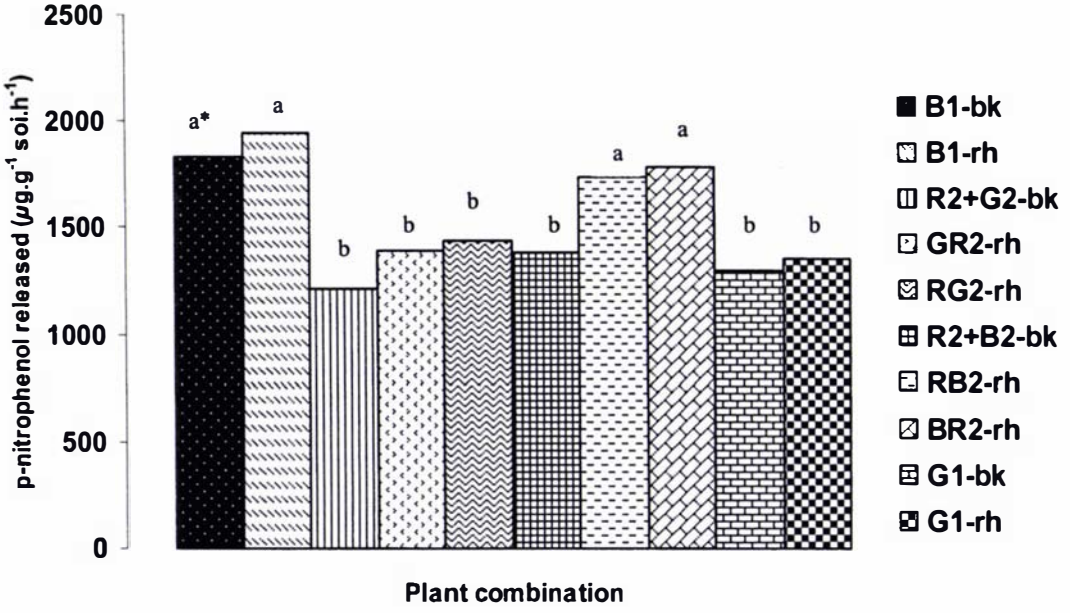

Figure 5.8 Acid phosphatase enzyme activity in rhizosphere and bulk soils under different plant combinations after 54 weeks of plant growth in an Allophanic Soil in a glasshouse
*Bars having the same letters at the top are not different at $P<0.05$

The rhizosphere and bulk soils under broom in compartment 1 (B_1-bk and B_1-rh) and the rhizosphere soil under radiata in association with broom in compartment 2 (BR_2-rh and RB_2-rh) had a significantly higher phosphatase enzyme activity than the soils under radiata in association with grass in compartment 2 (GR_2-rh and RG_2-rh) and under grass grown alone in compartment 1 (G_1-bk and G_1-rh). In addition, the phosphatase activity in the rhizosphere soil under broom grown alone in compartment 1 (B_1-rh) was slightly higher than that in the rhizosphere soil under radiata in association with broom in compartment 2 (BR_2-rh and RB_2-rh). These suggest that probably the presence of broom under radiata was also the cause for the increase in phosphatase activity in the rhizosphere soil of radiata. This is probably because higher N availability under the leguminous broom plant as a result of N_2 fixation by this legume may have enhanced soil phosphatase activity (Giardina *et al.*, 1995; Zou *et al.*, 1995). Also, N addition

through N_2 fixation by the broom may have increased the plants demand for P. Hence phosphatase activity increased to supply more P to the plants. Olander and Vitousek (2000) reported that in a N limited site in a chronosequence of soil in Hawaii, the addition of N stimulated phosphatase activity. They suggested that the stimulation of phosphatase activity by N addition could be through the direct use of N as building material for the production of N rich enzymes and indirectly through the increased productivity of the roots.

The high phosphatase activity in the rhizosphere soil when radiata was grown with broom could also be due to the interaction between radiata and broom rather than the effect of only the broom on the increase in phosphatase activity in radiata rhizosphere. The radiata also might have produced a high phosphatase enzyme by the ectomychorrizal radiata roots (Skinner and Bowen, 1974; Hauβling and Marschner, 1989; Antibus *et al.*, 1992; Scott, 2002). Zou *et al.* (1995) reported that soil phosphatase activity under red alder + mixed conifer stand was higher than that in the pure mixed conifer stand and red alder. However, in the present study it is difficult to assess whether the cause is interaction or not because there was no treatment of radiata grown alone.

The lack of marked differences in phosphatase activity between rhizosphere and the bulk soil in this study is probably due to a poor demarcation of boundary between the rhizosphere and the bulk soil region during the sampling of the soils – the bulk soil samples would have had some influence of roots because at the end of the experiment, plant roots had spread to all parts of the pots.

5.4.3 Soil P fractions

5.4.3.1 Resin-P_i

The resin-P_i concentration in the soils ranged from 0.9 to 2.6. μg P g^{-1} soil. This range is approximately close to the resin-P_i concentration values of 1.9 to 4.6 μg P g^{-1} soil

reported for Waikare clay loam soil from the north of Auckland, New Zealand (Comerford *et al.*, 2002). However, this range is much lower than the resin-P_i concentration values of 30 to 45 μg P g^{-1} soil reported for many other forest soils in USA (Spears *et al.*, 2001).

As observed in the field experiments (Chapter 3) it was expected that resin-P_i concentration would increase with P rates in the glasshouse trial because the soil had low plant-available P. However, neither the rates of P fertiliser addition nor the interaction of P rates and plant combination had any effect on resin-P_i concentration in the glasshouse trial soil. This is probably due to the soil in the glasshouse study was very P deficient (resin-P_i 1 μg P g^{-1} soil for control soil), hence, the plant roots would have depleted the increased amounts of resin-P_i at increased rates of P addition due to higher plant growth at the higher P rates (section 5.4.3.5). In addition, in the pot experiment the fertiliser-P added was mixed homogeneously in the soil. This probably may have increased P fixation to Fe and Al oxides and allophane (Clark and McBride, 1984; Parfitt, 1989) as seen from the very low resin-P_i concentration (< 2.5 μg P g^{-1} soil) in the glasshouse trial compared to high resin-P_i concentration in the filed trial (5-25 μg P g^{-1} soil).

Unlike P rates, plant combinations had a significant effect (p<0.0001) on the concentration of resin-P_i (Figure 5.9). The resin-P_i concentration in the rhizosphere soil of radiata in association with broom or grass (BR_2-rh, GR_2-rh) was significantly higher than that in the corresponding bulk soil (R_2+B_2-bk, R_2+G_2-bk), as well as in the rhizosphere soils of the associated plant (RG_2-rh and RB_2-rh) (Figure 5.5). This is probably related to organic anions (especially oxalate) released by radiata roots, which would have mobilized P in the rhizosphere (Malajczuk and Cromack, 1982; Fox and Comerford, 1992b; DeLucia *et al.*, 1997). This could also be due to the lower pH of radiata rhizosphere soil (Table 5.3). Increase of P availability following a decrease in soil pH has been reported by Hedley *et al.* (1982b) in a study with rape fertilised with KH_2PO_4 (Hedley *et al.*, 1982a). They explained that the increased P availability with a decrease in rhizosphere pH was due to an enhancement of P dissolution from acid-soluble forms of soil P_i. Still another reason for the increased resin-P_i concentration in

radiata rhizosphere is the higher phosphatase activity in radiata rhizosphere, which would have increased the rate of mineralisation of organic P, resulting in a higher concentration of labile inorganic P.

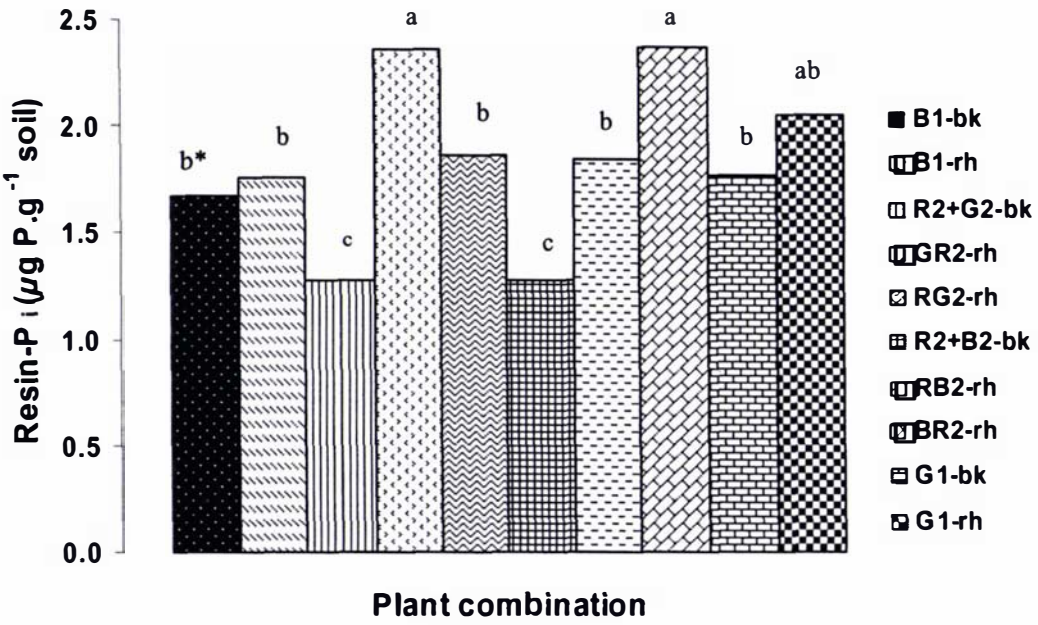

Figure 5.9 Effect of plant combinations on resin-P_i concentration ($\sqrt{Y}$ transformed data) after 54 weeks of plant growth in an Allophanic Soil in a glasshouse
* Bars having same letters at the top are not different at $P<0.05$

Some studies have shown that the resin-P_i concentration is lower in the rhizosphere than in the bulk soils because of the depletion of P in the rhizosphere by plant uptake (Trolove *et al.*, 1996; Zoysa *et al.*, 1998). The fact that resin-P_i is higher in the radiata rhizosphere in the current study indicates that the rate of P mobilisation in the rhizosphere was higher than the rate of P depletion by radiata.

The resin-P_i concentration was also higher in broom and grass rhizosphere (RB_2-rh and RG_2-rh) than in the bulk soils (R_2+G_2-bk and R_2+B_2-bk) when they were grown in association with radiata (compartment 2). This is probably due to the influence of the root processes of radiata and not that of grass or broom because there was no difference in resin-P_i between rhizosphere and bulk soils of broom (B_1-rh vs B_2-bk) or grass (G_1-rh vs G_2-bk) when they were grown alone (compartment 1). Similar patterns of differences between bulk and rhizosphere soils were observed for soil pH and phosphatase activity (section 5.4.1 and 5.4.2). These results are consistent with the findings of Fisher and Stones (1969) which showed that conifers increased available P in soils beneath or near the conifers and this resulted in a significant increase in P concentration in herbaceous plants beneath the conifers.

5.4.3.2 NaOH-P_i

Unlike the resin-P_i concentration, the 0.1 M NaOH-P_i concentration in both the bulk and rhizosphere soils under all plant combinations significantly (p=0.0012) increased with increased rates of P fertiliser application (Table 5.7). There were significant differences (p<0.0001) in 0.1 M NaOH-P_i concentration between plant combinations as well. The fertiliser rates and plant combination interaction effect on the 0.1 M NaOH-P_i concentration was also significant (p<0.0001).

Table 5.7 Main effect of TSP fertiliser on the NaOH-P_i concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

P rate (μg P g^{-1} soil)	NaOH-P_i concentration (μg P g^{-1} soil)
0	46.4 c
50	69.1 b
100	91.1 a
$lsd_{(p<0.05)}$= 11.6	

As Kaweka soil contains allophane and hence has a high P fixing capacity (Table 5.1), most of the fertiliser-P added would have been fixed to the soil (Clark and McBride, 1984; Parfitt, 1989) and this is reflected in the increase in NaOH-P_i concentration with an increase in rate of P application. The NaOH-P_i concentration increased more under grass than under broom, when these plants were grown alone (compartment 1) (Figure 5.11). The rate of increase of NaOH-P_i with an increased P rate in soils under radiata in association with grass (compartment 2) is also higher than that under radiata in association with broom (compartment 2) (Table 5.8, Figure 5.10). These differences in the rate of increase of NaOH-P_i are related to the difference in the growth of grass and broom because plants can utilise NaOH-P_i (Hedley *et al.*, 1982a; Trolove *et al.*, 2003) and plant having greater rate of growth can deplete NaOH-P_i in soil more than plants having low rate of growth. Broom grew at a faster rate with increased rates of P application than grass (see Chapter 6). Therefore broom per pot utilized a higher amount of applied P than grass (10.7 μg P g^{-1} soil vs 2.9 μg P g^{-1} soil, Chapter 6) leaving lower quantities of the added P in the soil.

Table 5.8 Effect of TSP fertiliser rate and plant combinations on NaOH-P_i concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

Plant combination	P fertiliser rate (μg P g^{-1} soil)		
	0	50	100
B_1-bk	39.1 c*	68.6 ab	70.4 e
B_1-rh	50.0 a	63.8 b	74.8 e
R_2+G_2-bk	48.8 abc	64.9 b	96.6 bc
GR_2-rh	39.7 bc	74.0 ab	95.6 bcd
RG_2-rh	51.1 a	67.2 ab	99.0 b
R_2+B_2-bk	46.9 abc	64.4 b	88.7 cd
RB_2-rh	48.1 abc	70.5 ab	90.7 bcd
BR_2-rh	45.4 abc	73.8 ab	85.7 d
G_1-bk	49.6 ab	67.4 ab	99.2 b
G_1-rh	45.3 abc	76.6 a	110.7 a
$lsd_{(p<0.05)} = 10.3$ *(plant combination)*			

*Numbers under each P rate followed by the same letters are not different at $P<0.05$

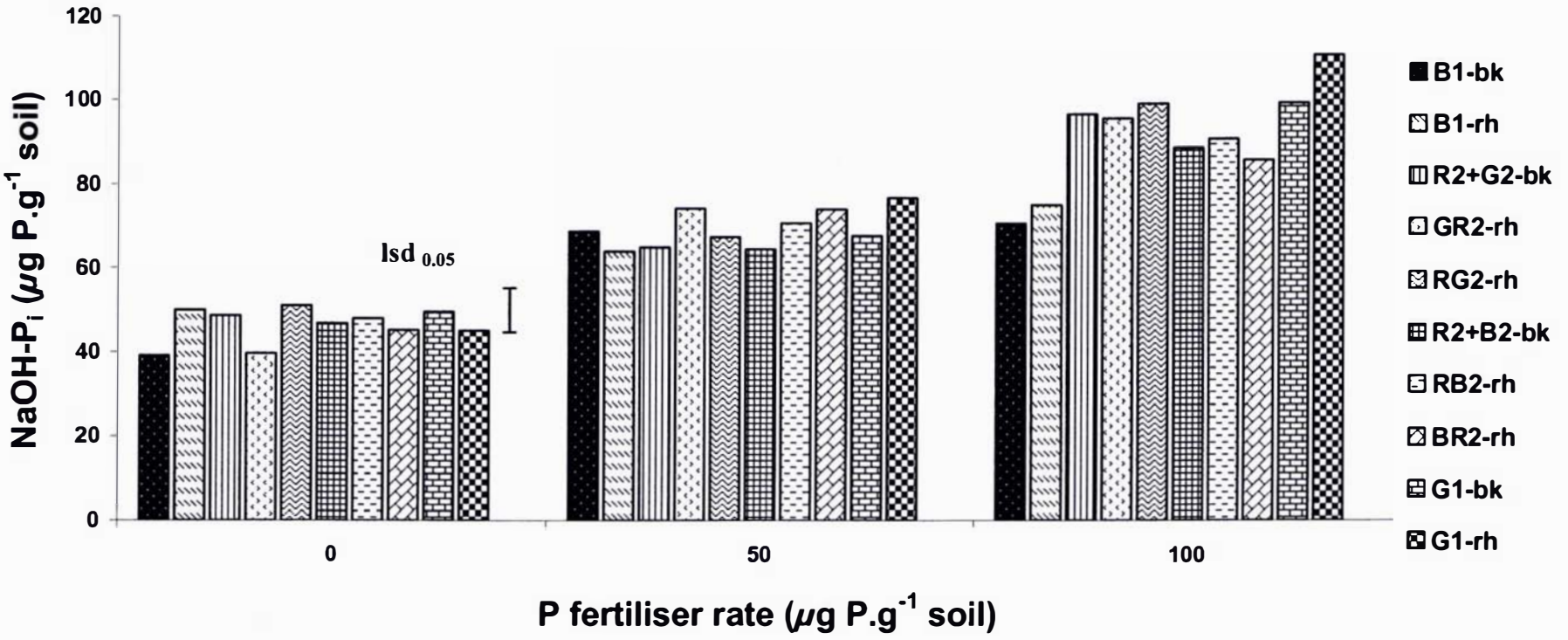

Figure 5.10 Effect of TSP fertiliser rates and plant combinations on NaOH-P_i concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse ($lsd_{(p<0.05)} = 10.3$ for plant combinations)

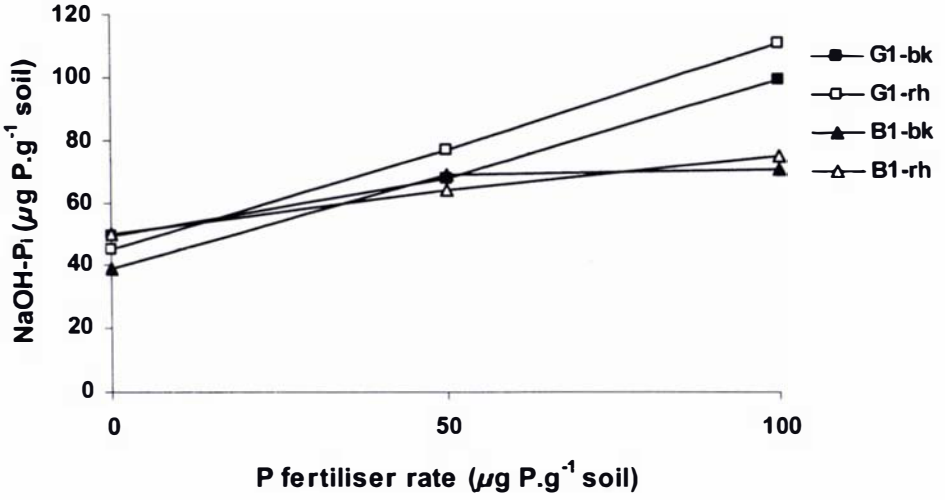

Figure 5.11 Effect of TSP fertiliser rate on NaOH-P_i concentration after 54 weeks of plant growth in an Allophanic Soil under grass and broom when they were grown alone (compartment 1) in a glasshouse

The plant combinations and P rate interaction was significant for NaOH-P_i in the rhizosphere of grass and radiata when zero P treatment was compared with other P rates. The concentrations of 0.1 M NaOH-P_i in rhizosphere soils of radiata (GR_2-rh and BR_2-rh) were approximately the same as in the rhizosphere soils of the two associated plants (RG_2-rh and RB_2-rh) for the P application rates of 50 and 100 μg P g^{-1} soil. But when no P was applied, the NaOH-P_i concentration was significantly lower in the radiata rhizosphere soil (GR_2-rh) than in the rhizosphere soil of grass (RG_2-rh) in compartment 2. This is probably because under P deficient condition, the radiata root mycorrhizae is most active in producing oxalates (Malajczuk and Cromack, 1982; DeLucia *et al.*, 1997) which may have released P_i fixed to allophane and Fe and Al oxides resulting in a decrease in NaOH-P_i concentration in rhizosphere soils.

The NaOH-P_i concentration in the rhizosphere of broom was, however, not higher than that in radiata when no P was applied. This is perhaps due to the higher uptake of P by broom than that by grass (Chapter 6).

5.4.3.3 NaOH-P_o

The labile P_o (NaOH-P_o) was the largest P pool in the soil, containing 127 to 146 μg P g^{-1} soil (48 to 54% of the total soil P concentration). Increased rates of P fertiliser application significantly (p=0.012) increased the NaOH-P_o concentration in soils (Table 5.9) but the extent of the increase was less than that of the NaOH-P_i concentration (Table 5.7). This shows that the proportion of P applied to the soil that was converted to the labile organic P pool was less than what was absorbed to allophane and Fe+Al oxides.

Table 5.9 Main effect of TSP fertiliser on NaOH-P_o concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

P rate (μg P g^{-1} soil)	NaOH-P_o concentration (μg P g^{-1} soil)
0	123.1 b
50	127.9 b
100	142.1 a
$lsd_{(p<0.05)}$= 9.59	

*Numbers followed by the same letters are not different at P<0.05

The increase in NaOH-P_o concentration with an increase in P rates could be due to increased root growth (see Chapter 6) which might have increased soil organic matter content from the decay of dead roots and hyphal materials. Condron and Goh (1989) reported that a significant proportion of P in superphosphate, applied annually for 20 years to a Lismore silt loam (Udic Ustochrept) soil under intensively grazed irrigated pasture, was converted to organic P. They suggested that this was probably related to

the biological immobilization of soil inorganic P via plant, animal and microbial residues.

There were significant (p<0.0001) differences in the concentration of NaOH-P_o between plant combinations. The interaction between the P fertiliser rate and plant combination was also significant (p=0.011) (Table 5.10 and Fig 5.12).

When no P was applied (0 TSP), the concentration of NaOH-P_o in the rhizosphere soil of broom grown alone (B_1-rh) was significantly (p<0.05) lower than that in the bulk soil (B_1-bk) (Table 5.10 and Figure 5.12), while, the NaOH-P_i concentration was higher in broom rhizosphere soil than in the broom bulk soil (Table 5.8 and Figure 5.10). This suggests that under P deficient conditions the phosphatase enzyme in the rhizosphere was very active and it converted labile organic P to inorganic P (Tarafdar and Junk, 1987). This trend was, however, not observed at high rates of P (Table 5.10 and Figure 5.12) although, at a 100 TSP treatment, the NaOH-P_o concentration was again lower in the broom rhizosphere than in the broom bulk soil.

Table 5.10 Effect of TSP fertiliser rate and plant combinations on NaOH-P_o concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

Position	P rate (μg P g^{-1} soil)		
	0	50	100
B_1-bk	134 a*	121 c	165 a
B_1-rh	118 bc	123 c	147 b
R_2+G_2-bk	123 abc	126 c	127 c
GR_2-rh	123 abc	116 c	138 bc
RG_2-rh	120 abc	128 bc	128 c
R_2+B_2-bk	120 abc	128 bc	141 bc
RB_2-rh	115 c	123 c	141 bc
BR_2-rh	114 c	126 c	144 b
G_1-bk	131 ab	147 a	152 ab
G_1-rh	134 a	142 ab	139 bc
$lsd_{(p<0.05)}$= 15 (plant combination)			

*Numbers within each P rate followed by the same letters are not different at $P<0.05$

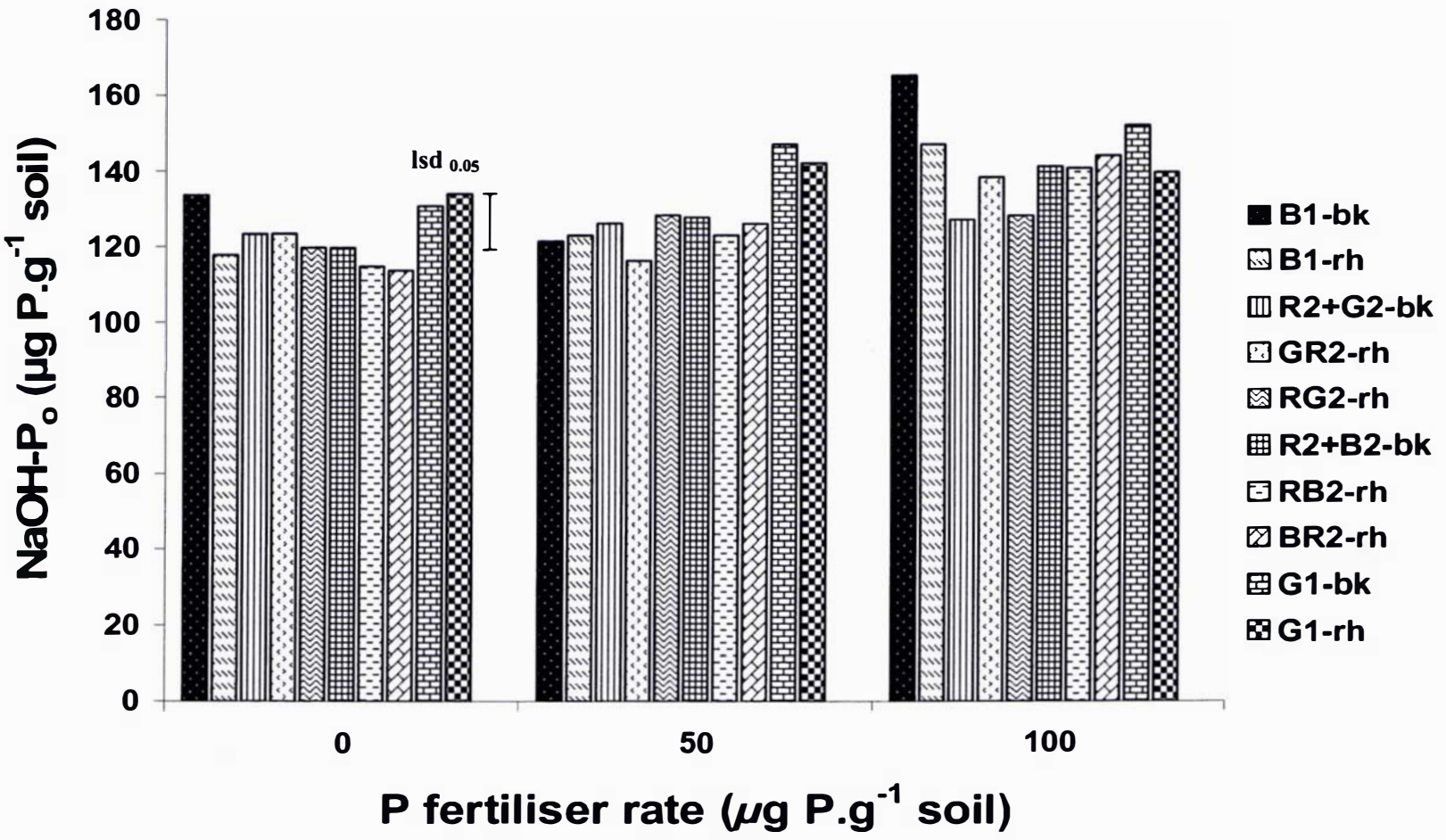

Figure 5.12 Effect of TSP fertiliser rate and plant combinations on NaOH-P_o concentration after 54 weeks growth in an Allophanic Soil in a glasshouse ($lsd_{(p<0.05)}$= *15 (plant combinations)*

There was no significant difference in the NaOH-P_o concentration between the bulk and rhizosphere soils of radiata and grass. However, Liu *et al.* (2004b) reported that under field conditions the NaOH-P_o concentration was higher in the rhizosphere of radiata than in the bulk soil. He explained this difference as due to a higher concentration of organic carbon as a result of long-term root and hyphae decomposition in the rhizosphere.

The NaOH-P_o concentrations in the radiata rhizosphere soils were not different from those in the rhizosphere soils of the associated plants and the corresponding bulk soils. This is consistent with the phosphatase activity results where no difference was observed between radiata rhizosphere soils and the associated plant rhizosphere soils. There was also no difference in the effect of plant species on NaOH-P_o concentrations in radiata rhizosphere (GR_2-rh vs BR_2-rh). However, Scott (2002) reported that total organic P extracted in lucerne-tree rhizosphere soil under field conditions was significantly less than ryegrass-tree soil and this lower P concentration was associated with a higher level of phosphatase enzyme activity (acid and alkaline) and phosphodiesterase activity.

5.4.3.4 H_2SO_4-P_i

P application significantly (p=0.0002) increased the concentration of H_2SO_4-P_i in the soil (Figure 5.13), but the magnitude of the increase was lower than that of NaOH-P_i (Figure 5.10) and NaOH-P_o (Figure 5.12). The effects of plant combinations and the interaction of P fertiliser rates and plant combinations on H_2SO_4-P_i concentrations were also significant (p=0.0001 and p=0.0487, respectively) (Figure 5.13).

When TSP is applied to soil, part of the monocalcium phosphate in TSP is converted to dicalcium phosphate at the soil/fertiliser interface. In the long term these phosphates get converted into mostly amorphous Fe, Al-phosphates and trace amounts of Ca-phosphates (Lehr *et al.*, 1959). The H_2SO_4 extraction gives a measure of this calcium-bound P.

At 0 and 100 μg P g^{-1} rates of application, the concentration of H_2SO_4-P_i was significantly lower in the rhizosphere soil of broom alone, than in the rhizosphere soils of radiata grown with grass or broom and grass alone (B_1-rh vs GR_2-rh, BR_2-rh and G_1-rh). This is probably because of the higher growth rate of broom compared to that of radiata and grass (Chapter 6) resulting in higher amounts of plant uptake of Ca from the broom rhizosphere thus decreasing the Ca-bound P extracted by H_2SO_4. Such difference in H_2SO_4-P_i concentration was not observed for the 50 μg P g^{-1} rate. The values were generally lower in the rhizosphere of broom, but were not statistically significant.

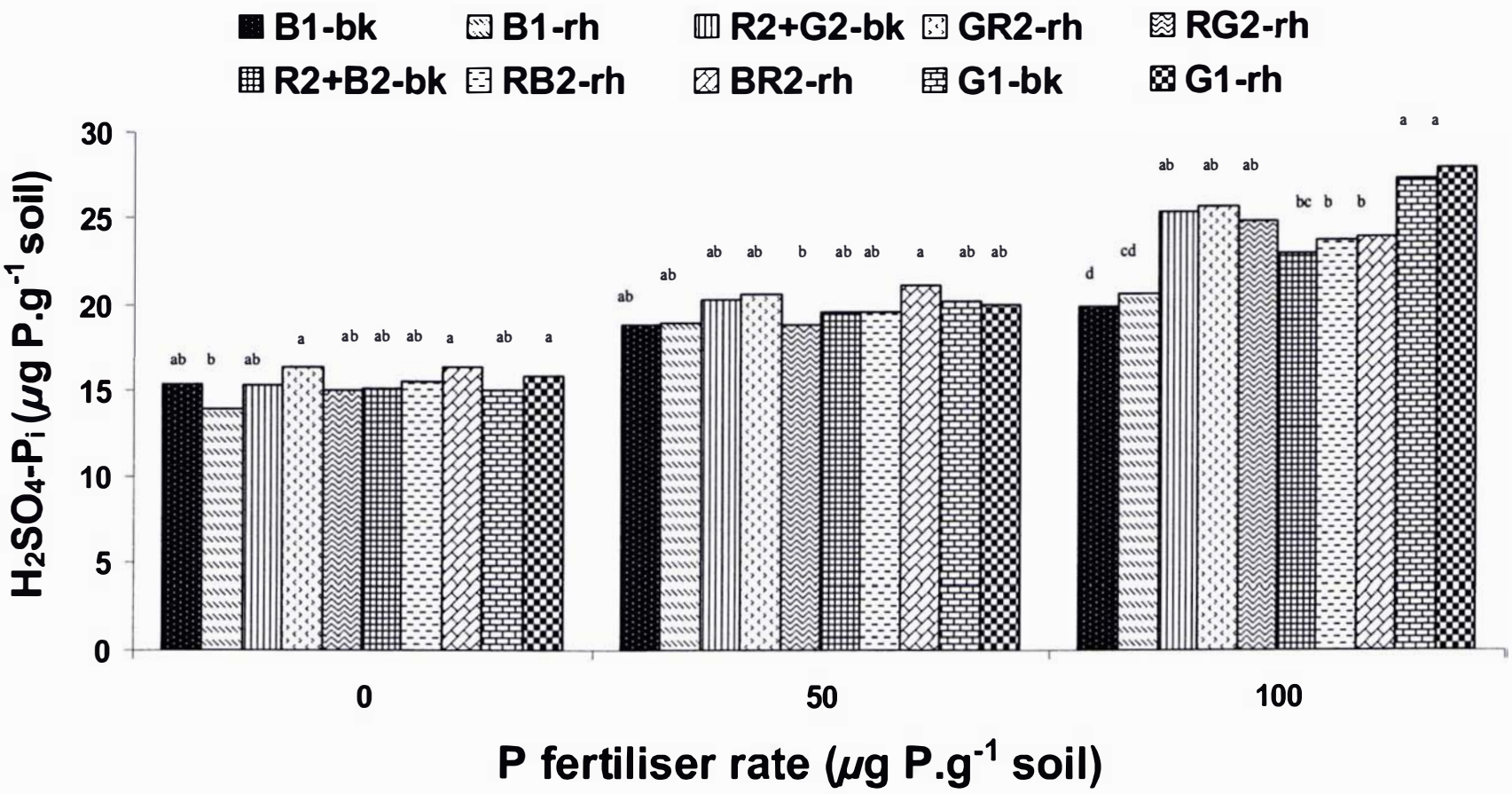

Figure 5.13 Effect of TSP fertiliser rates and plant combinations on H_2SO_4-P_i concentration after 54 weeks growth in an Allophanic Soil in a glasshouse ($\log_e$ Y transformed data)
*Bars within each P rate having the same letters at the top are not different at $P<0.05$ (for plant combinations)

5.4.3.5 Residual-P

Fertiliser addition at the rates of 50 and 100 μg P g^{-1} soil significantly (p=0.0150) decreased the concentration of residual-P from 45 to 41 μg P g^{-1} soil (Figure 5.14). The actual magnitude of this depletion is, however, small. The increased residual-P depletion at increased rates of P fertiliser application suggests that the added P in fertiliser had not entered the residual-P pool, but, to the contrary, plants have mobilized some of the residual-P by the increased growth of roots and mycorrhizae resulting from higher plant growth at higher P rates. Plants are reported to improve their accessibility to total soil P resources through the increased absorption area of the root system (Barber, 1995) or increased association with mycorrhizae (Marschner and Dell, 1994; Brandes *et al.*, 1998). Plant uptake of P from the residual-P fraction has been reported in literature. For example, Gahoonia and Nielsen (1992) reported that 15-18% of total P depletion by rape grown on sandy silt loam soil, fertilised with a complete nutrient solution, was from the residual-P fraction in the soil.

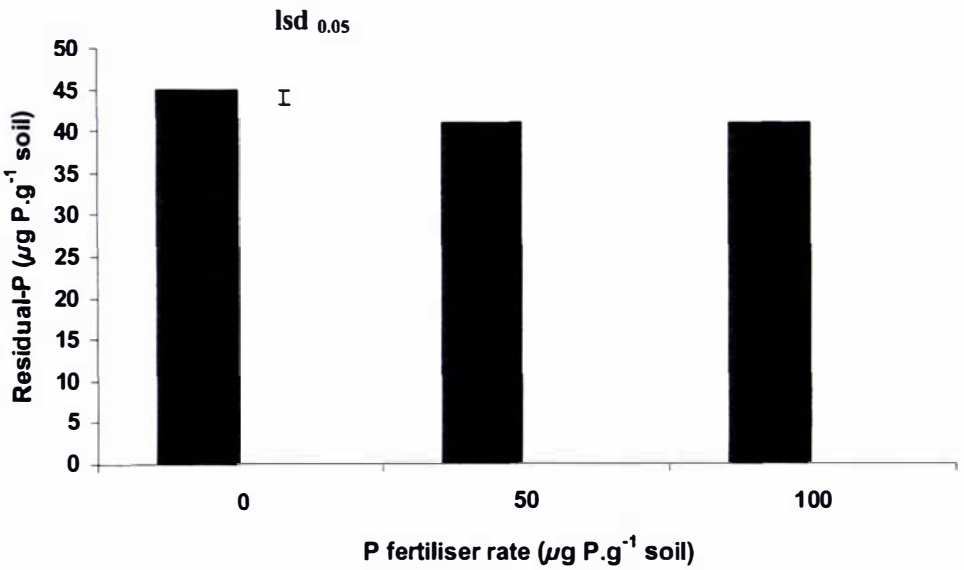

Figure 5.14 Effect of TSP fertiliser rate on residual-P concentrations after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

The effect of plant combinations on the concentration of residual-P in the soil was also significant (p=0.0248), but the magnitude of the effect was very small (Figure 5.15). There was no significant interaction between the P fertiliser and plant combinations on the residual-P concentration. The residual-P concentration in the rhizosphere soil of radiata grown with broom (BR_2-rh) was lower than that in the rhizosphere soil of radiata grown with grass (GR_2-rh). Also, broom alone (B_1-bk, B_1-rh) had a lower residual-P concentration than grass alone (G_1-bk, G_1-rh). These differences are consistent with the differences in the growth rate between grass and broom (Chapter 6). Broom had a higher growth rate than grass, and, therefore, extracted more residual-P. Scott (2002) also reported that radiata grown with lucerne in an Immature Pallic Soil produced a greater decline in the recalcitrant P pool (the difference between total P concentration and total inorganic P concentration) than when radiata was grown alone, lucerne grown alone, ryegrass grown alone and radiata grown with ryegrass. He explained that this was due to a higher P uptake by radiata and lucerne as a result of the greater total biomass production when they were grown together.

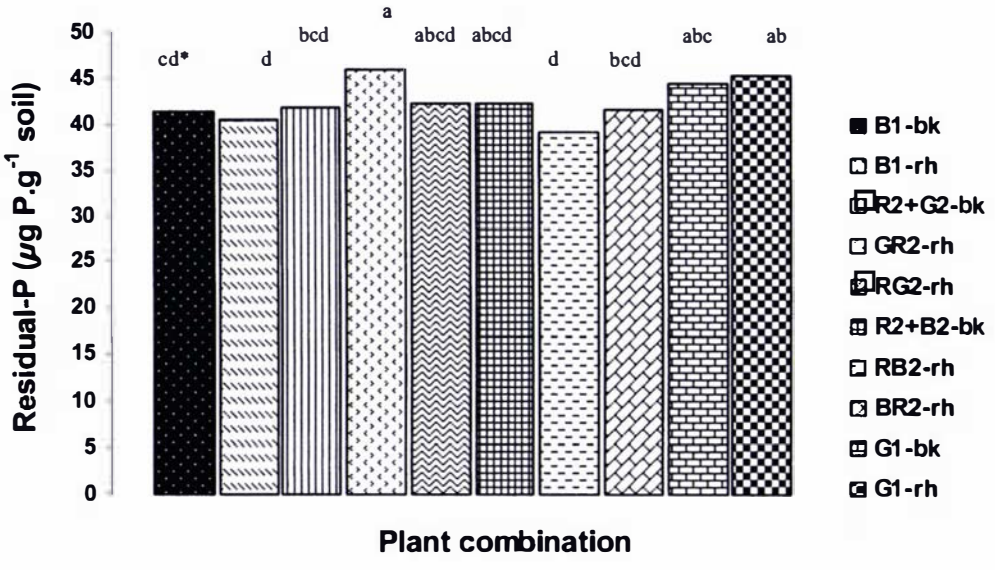

Figure 5.15. Effect of plant combinations on the residual-P concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse
*Bars having the same letters at the top are not different at P<0.05

5.4.4 Proportion of fertiliser P in the different soil P fractions

The soil P fractionation at plant harvest showed that the P concentration in the different P fractions decreased in the order of NaOH-P_o > NaOH-P_i > residual-P > H_2SO_4-P_i > resin-P_i in both the bulk and the rhizosphere soils averaged over all treatments (Figure 5.16). The pattern of change in P concentration in the different P fractions as the P fertiliser rate was increased was the same for the bulk and the rhizosphere soils. Increased P fertiliser rates increased the concentration of NaOH-P_i, NaOH-P_o, and H_2SO_4-P_i fractions in the soil, decreased the concentration of residual-P and had no effect on the concentration of resin-P_i. The possible reasons for these trends have already been discussed in section 5.4.3.

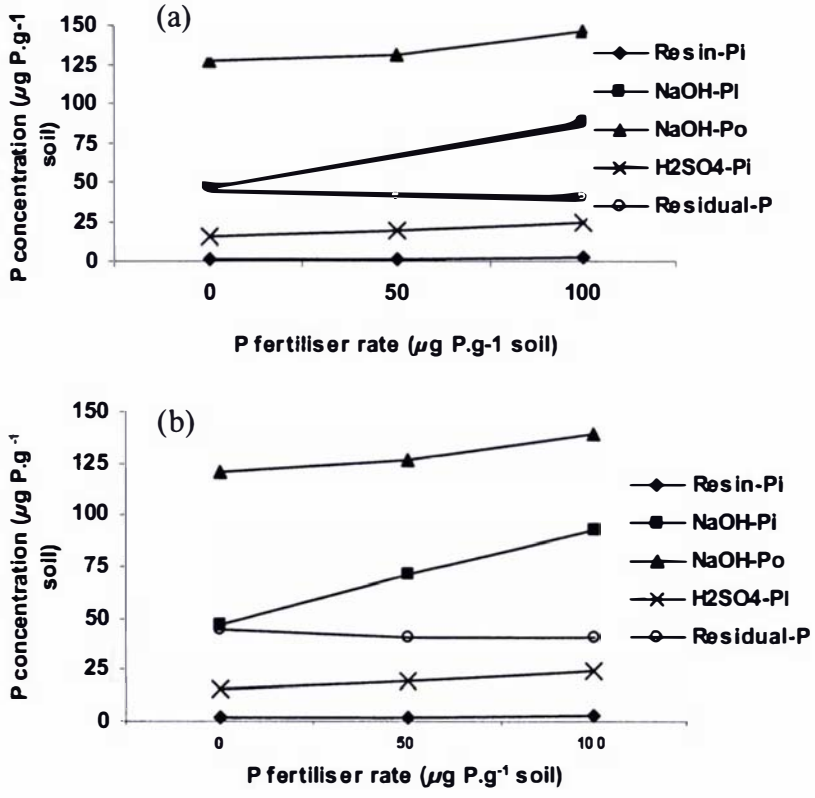

Figure 5.16 Comparison of the change in P concentration in the different soil P fractions with an increase in TSP fertiliser rate in (a) the bulk soil, and (b) the rhizosphere soil, averaged over all treatments after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

The recovery of P added in fertiliser in the different soil P fractions, in both the bulk and the rhizosphere soils averaged over all plant combinations, ranged from 49 to 71%. The majority of the unaccounted fertiliser P is recovered in plants. This is discussed in Chapter 6. Table 5.7 shows that the NaOH-P_i fraction constituted the highest percentage of P (40-49%) derived from the added P fertiliser. This is due to the very high P retention capacity (92%) of the Allophanic Soil used in this study (Clark and McBride, 1984; Parfitt, 1989). The next highest recovery was in the NaOH-P_o fraction (7-19%).

Unlike the findings of Trolove *et al.* (1996) and Zoysa *et al.* (1997) on soils with low P fixing capacities, in this study the P recovery of fertiliser P in the resin-P_i pool is extremely low ($\leq$1%) due to the high P fixing capacity of this soil (Table 5.11). The above workers reported P recoveries in the resin-P_i pool of 13 to 30%.

Table 5.11 The % recovery of added P in each of the P fractions in the bulk and the rhizosphere soils averaged over all plants after 54 weeks of plant growth in an Allophanic Soil in a glasshouse[1]

P fraction	Bulk soil P fertiliser rate (μg P g^{-1} soil)		Rhizosphere soil P fertiliser rate (μg P g^{-1} soil)	
	50	100	50	100
	---------- % ----------		---------- % ----------	
Resin-P_i	0.3	0.8	0.3	1.0
NaOH-P_i	40.4	42.6	48.8	46.1
NaOH-P_o	7.0	19.2	11.4	18.9
H_2SO_4-P_i	9.1	8.6	8.6	8.9
Residual-P	-7.4	-4.5	-8.2	-3.7
Total	49.4	66.7	60.9	71.2

[1] $\frac{\text{(P concentration } (\mu g\ P\ g^{-1}\ soil) \text{ in fertilised soil - P concentration } (\mu g\ P\ g^{-1}\ soil) \text{ in control soil)}}{\text{Fertiliser P added to soil } (\mu g\ P\ g^{-1}\ soil)} \times 100$

* The % recovery of added P in plants will be discussed in Chapter 6

5.4.4 Soil plant-available P

5.4.4.1 Bray-2 P

The soils that received no P fertiliser had very low Bray-2 P concentrations (approximately 3 μg P g^{-1}) (Figure 5.17). 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). This is due to the high fixation of P by this Allophanic Soil.

The increase of the P fertiliser rate significantly (p<0.0001) increased Bray-2 P concentrations, both in the rhizosphere and the bulk soils under all plant combinations (Figure 5.17). The highly significant effect of the P fertiliser rate on the Bray-2 P concentrations is not surprising as the soils without P addition had a low plant-available P concentration. This is in contrast to the resin-P_i concentration, which did not change with increased P rates (section 5.4.3.1). The difference in the effect of P rates on Bray-2 P and resin-P_i concentrations is due to the difference in the form of P extracted by these two extractants. The Bray-2 reagents are stronger extractants dissolving much of the fixed P compared to the milder resin extractant, which removed mostly the weakly adsorbed P. Bray-2 P soil test extractants 0.03 M NH_4F + 0.1 M HCl dissolve most of the Ca-P and Al+Fe-P (Mehlich, 1978). The pattern of increase in Bray-2 P concentrations with increased P fertiliser rates is similar to that of NaOH-P_i concentrations (Figure 5.10). Furthermore, the NaOH-P_i pool had the highest concentration of fertiliser P and it is very highly correlated with Bray-2 P (Table 5.12). This suggests that Bray-2 P may be extracting mainly the NaOH-P_i fraction, as reported by Hahne *et al.* (1988).

H_2SO_4-Pi also had a very high correlation with Bray-2 P, probably, because it is strongly related to NaOH-P_i (Table 5.12).

Significant (p<0.0001) differences in Bray-2 P concentrations between plant combinations were also observed. The interaction between P fertiliser rates and plant combinations was significant as well (p=0.0004).

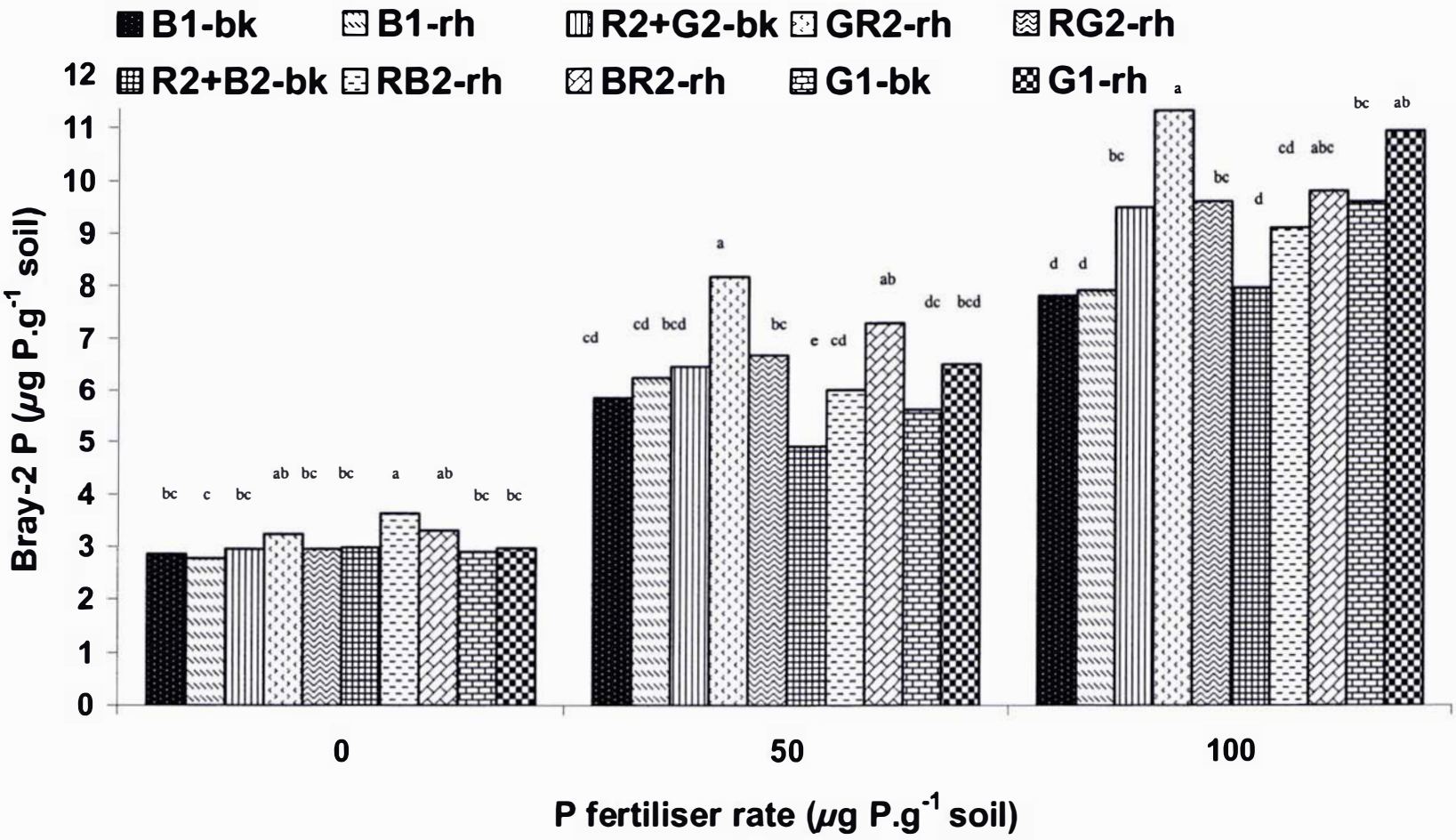

Figure 5.17 Effect of TSP fertiliser rate and plant combinations on Bray-2 P concentrations after 54 weeks growth in an Allophanic Soil in a glasshouse ($\log_e$ Y transformed data)
*Bars within each P rate having the same letters at the top are not different at $P<0.05$

Table 5.12 Correlation matrix for Bray-2 P and P fractions for all rates of TSP fertiliser and plant combinations after 54 weeks of plant growth in an Allophanic Soil in a glasshouse

	Bray-2 P	**Resin-P_i**	**NaOH-P_i**	**NaOH-P_o**	**H_2SO_4-P_i**	**Residual-P**
Bray-2 P	1					
Resin-P_i	0.72***	1				
NaOH-P_i	0.96***	0.65**	1			
NaOH-P_o	0.51**	0.43*	0.48**	1		
H_2SO_4-P_i	0.96***	0.68***	0.97***	0.51**	1	
Residual-P	-0.39*	-0.00	-0.33	-0.11	-0.24	1

* Correlation coefficient significant at $P<0.05$
** Correlation coefficient significant at $P<0.01$
*** Correlation coefficient significant at $P<0.001$

In general, the Bray-2 P concentrations in the rhizosphere soil of radiata is higher than that in the rhizosphere soils of the associated plants (GR_2-rh > RG_2-rh and BR_2-rh > RB_2-rh). This indicates that radiata can help to increase soil P availability to the associated plants in high P fixing, P deficient soils. For each of the P rates, the Bray-2 P concentration in rhizosphere soils of radiata is higher than that in the bulk soil regardless of the associated plant (GR_2-rh > R_2+G_2-bk and BR_2-rh > B_2+R_2-bk). This suggests that radiata roots are mobilizing P, probably, by acidifying the soil, solubilising fixed P and converting organic P to inorganic P as discussed in previous sections.

The Bray-2 P concentration in the rhizosphere soil of radiata in association with broom (BR_2-rh) was consistently lower than that in the rhizosphere soil of radiata in association with grass (GR_2-rh) for the P rates of 50 and 100 μg P g^{-1} soil. This is, probably, due to higher P uptake by broom than grass (Chapter 6), causing a higher depletion of Bray-2 P.

5.4.4.2 Resin-P_i (*in situ* measurement)

The main effects of P fertiliser rates (p=0.0397) and plant combinations (p=0.0032) on P extracted by HCO_3^--saturated resin strips inserted into the soil in the trays with plants were significant. There was no P fertiliser rate x plant combination interaction effect.

Application of 50 and 100 μg P g^{-1} soil significantly increased the resin-P_i concentrations in the soil. However, the magnitude of the increase was very small and there was no significant difference in resin-P_i concentrations between the application rates of 50 and 100 μg P g^{-1} (Figure 5.18). These results are consistent with those obtained for resin-P_i concentrations in the soil P fractionation analyses (section 5.4.3) where resin-P_i concentrations were very low and again did not change from 50 to 100 μg P g^{-1} soil application rates. In the soil P fractionation analyses there was also no change in resin P between 0 and 50 μg P g^{-1} additions.

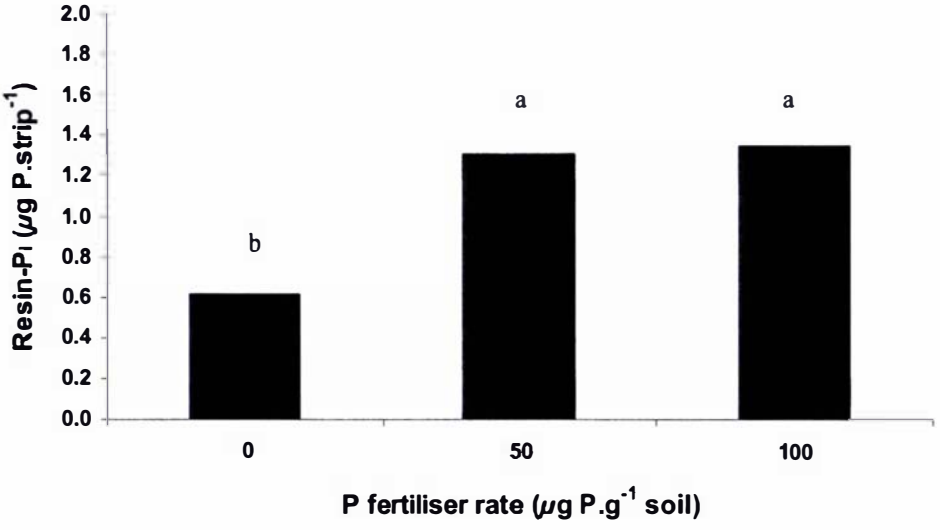

Figure 5.18 Effect of TSP fertiliser rate on resin-P concentration after 54 weeks of plant growth in an Allophanic Soil in a glasshouse ($\sqrt{Y}$ transformed data) *Bars having the same letters at the top are not different at P<0.05

As observed for Bray-2 P (section 5.4.4.1), the concentration of resin-P_i in the soil under radiata in association with broom (compartment 2) was significantly lower than that in

the soil under radiata in association with grass (compartment 2). Also, the resin-P_i concentration in the soil under broom alone (compartment 1) was significantly lower than that in the soil under grass alone (compartment 1) (Figure 5.19). These findings are probably due to the higher P uptake by the broom compared to the grass (see Chapter 6) resulting in the broom depleting more of the resin-P_i pool.

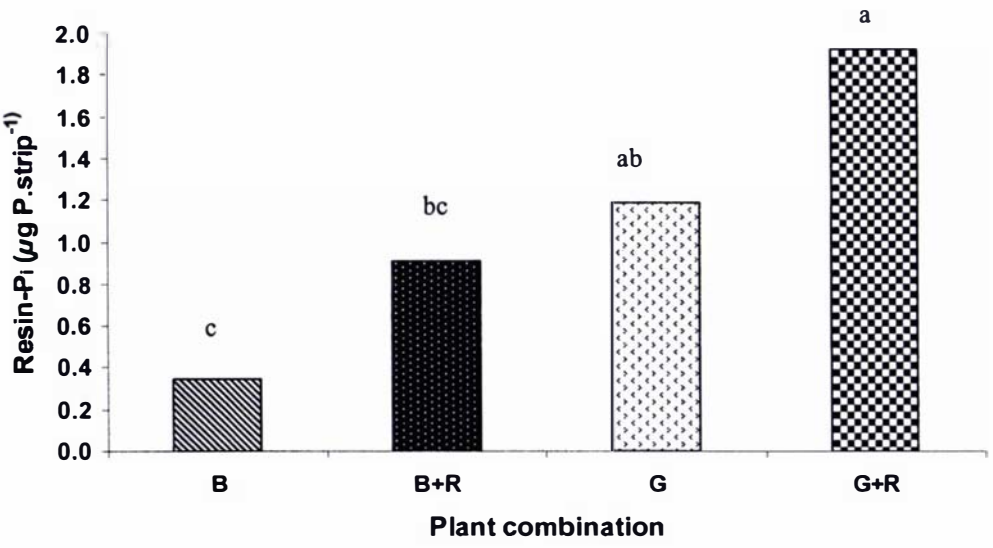

Figure 5.19 Effect of plant combinations on resin-P_i concentrations after 54 weeks of plant growth in an Allophanic Soil in a glasshouse ($\sqrt{Y}$ transformed data)
*Bars having the same letters at the top are not different at $P<0.05$

The concentrations of resin-P_i in soils under radiata with the associated plants (compartment 2) were higher (but not significantly different at $p<0.05$) than those in soils under the associated plants grown alone in compartment 1 (R+B vs B and R+G vs G, Figure 5.19), even though the plant uptake of P per g soil (29.9 μg P g^{-1} in compartment 2 versus 10.7 μg P g^{-1} in compartment 1 and 25.2 μg P g^{-1} in compartment 2 versus 2.9 μg P g^{-1} soil in compartment 1) was higher in compartment 2 (see Chapter 6). This suggests that the presence of radiata helps to enhance P availability in the soil. This is consistent with the finding of Fisher and Stones (1969) that conifers increased P availability in the soil beneath or near the conifers. These results are consistent with

those of other studies where there were increases in inorganic P, Olsen P and Bray P following land-use change from grassland to pine plantation (Davis and Lang, 1991; Davis, 1995; Condron *et al.*, 1996; Chen *et al.*, 2000; Scott, 2002; and Chen *et al.*, 2003).

5.5 Conclusions

Phosphate fertiliser application enhanced root induced acidification in the rhizosphere of radiata seedlings in a P deficient Allophanic Soil. The soils in the rhizosphere of grass and broom, grown in association with radiata, were also acidified by the effect of radiata roots. This acidification caused increased P availability in the rhizosphere soils as measured by Bray-2 P and resin soil P tests.

Acid phosphatase activity in soils under radiata, grass and broom decreased with an increased rate of P application, in agreement with other studies reported in the literature. At all P rates, acid phosphatase activity was higher in the rhizosphere of radiata grown with broom than in the bulk soils. The phosphatase activity in the rhizosphere soil of radiata grown with broom was higher than that of radiata grown with grass. These results suggest that broom may have also contributed to the higher phosphatase activity in the rhizosphere soils than in the bulk soils of broom and radiata when they were grown together. This effect of broom is probably due to N_2 fixation by this plant which may have increased N availability to radiata, thereby, increased P availability through production of phosphatase enzymes. There is also possibility that the increase in phosphatase activity could be due to the interaction between radiata and broom, but it can not be assessed in this study because the trial had no treatment where radiata was grown alone.

Acid phosphatase activity measured in the laboratory using *p*-nitrophenyl phosphate as the substrate may not give an accurate information on the phosphatase activity in the field because of different types of substrates in field soils. Furthermore the phosphatase activity depends on the availability of substrate and it is always the substrate concentration which limits the phosphatase activity. For example, the phosphatase

activity determined in the laboratory was up to 13 μmole *p*-nitrophenol g^{-1} soil per hour, whereas the total Po in the field soil was < 200 μg P g^{-1} soil or < 7 μmole P_o g^{-1} soil.

The soil used in the trial had NaOH-P_o (127 μg P g^{-1} soil and 50.2% of total P) as the largest P fraction. Application of P fertiliser increased NaOH-P_i, NaOH-P_o, and H_2SO_4-P_i concentrations in the soil, but decreased the residual-P concentration. The resin-P_i concentration, which is extremely low in this soil (1 to 3 μg P g^{-1} soil), remained the same.

The majority of the added fertiliser P was however recovered in the NaOH-P_i fraction (40-49%). This is due to the high P fixation in this soil (92%). The second highest recovery was in the NaOH-P_o fraction (7-19%). The NaOH-P_i concentration had a very high correlation with Bray-2 P concentration, indicating that even though P fixation in the soil is high, some of the fixed P may be available to plants. NaOH-P_o, though not immediately available to plants, may become available in the long-term.

The NaOH-P_i concentration in the radiata rhizosphere soil was lower than in the bulk soil and broom and grass rhizosphere soils under P deficient conditions (when no P fertiliser was applied). This may have been due to higher oxalate production by the roots and mycorrhiza under P deficient conditions which released some of the P fixed to the soils in the rhizosphere. This suggestion needs to be tested in future radiata rhizosphere studies.

Attempts will be made to use the results reported in this chapter to explain the P uptake characteristics

Chapter 6

Synergistic and Antagonistic Effects of Broom and Ryegrass on P Nutrition of *P. radiata* Seedlings - Growth and P Nutrition

6.1 Introduction

The results from Chapter 5 showed that increased acidification occurred in radiata rhizosphere soil compared to bulk soil whether radiata was grown in association with broom or with ryegrass. The presence of radiata also induced acidification in the rhizosphere soils of broom and ryegrass. Broom appeared to have increased acid phosphatase activity in the rhizosphere of radiata when these two plants were grown together. This was thought to be due to increased N supply resulting from N fixation by broom. There was also evidence that radiata enhanced the plant-availability of soil P in the rhizosphere as measured by Bray-2 P and resin-P_i soil tests. In this chapter the effect of these changes on dry matter yield and P nutrition of radiata, broom, and ryegrass are presented. Attempts are made to compare the effect of broom and ryegrass on the growth and P nutrition of radiata. The results of this study are expected to give a better understanding of the P uptake and growth of radiata in association with understorey plant species, under different soil P levels. This information is useful for a better management of P fertility in forest plantations.

6.2 Objectives

The objectives of the study reported in this chapter are:

1. To compare the effect of broom and ryegrass grown with radiata seedlings in an Allophanic Soil treated with three rates of TSP on the growth and P nutrition of radiata in the glasshouse trial described in Chapter 5.
2. To determine relationships of soil P fractions, and plant-available soil P concentrations with dry matter yield and P concentration in radiata needles and broom and ryegrass shoots.

6.3 Materials and methods

6.3.1 Trial design and conduct

The trial design and conduct were described in Chapter 5. This design allows a comparison to be made on radiata growth and P nutrition when radiata was grown with broom as compared to ryegrass.

6.3.2 Harvesting

Ryegrass was harvested twice during the trial – firstly at 22 weeks (20 September 2002), and secondly, at the end of the experiment at 42 weeks (21 February 2003) after the ryegrass seeds were sown. Broom and radiata were harvested only at the end of the experiment at 54 weeks (22 February 2003) after planting these seedlings.

Radiata, broom and grass shoots 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 (new shoot needles). Old shoot needles and stem were also retained. The stems and needles were dried in an oven at 65°C for 48 hours and the dry weights were recorded.

After removing the rhizosphere soils as described in Chapter 5, the roots of all three plant species were washed free of soil and dried in an oven at 65°C for 48 hours and the dry weights were recorded.

The dried needles, stem, shoot 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 concentrated sulphuric acid (95-97%) (Twine and Williams, 1971). Nitrogen and P concentrations in the digest were measured by using a Technicon auto-analyser (Searle, 1975).

6.3.3 Statistical analysis

Analysis of variance (ANOVA) for a split-plot design was performed using SAS (SAS Institute, 2001). The least significant difference (LSD) test at $P<0.05$, unless otherwise stated, was used to separate the means when 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).

6.4 Results and discussion

6.4.1 P concentration in plants

6.4.1.1 Radiata

The P concentration in new shoot needles was higher than those in old shoot needles, stem and roots (Table 6.1). Similar findings were reported by Liu *et al.* (2004a). The P concentration in new shoot needles of radiata grown with grass 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 Will, 1976; Will, 1978). The P concentration in old shoot needles was however lower than this threshold P concentration for all P treatments. Phosphorus concentrations in new shoot needles, old shoot needles, stem and roots of radiata were significantly influenced by the rate of P fertiliser application ($p<0.0001$, $p<0.0001$, $p=0.0016$, and $p=0.0038$, respectively) (Table 6.1). The interaction of P fertiliser and plant combination on P concentration in all these plant organs was also significant ($p=0.0145$ for new shoot needles, $p=0.0105$ for old needles, $p=0.0307$ for stem, and $p=0.0369$ for roots)

Increased P fertiliser rates significantly increased P concentration in new shoot needles, old shoot needles, stem and roots of radiata regardless of the plant association (Table 6.1). This is consistent with the effect of P rates on plant available P concentration in the soil reported in Chapter 5. Liu *et al.* (2004a) also reported increased P concentration in different parts of shoots of seedlings grown on soil taken from the same forest plantation with increased rates of P application.

Table 6.1 Effect of TSP fertiliser rate and plant combination interaction on P concentration (%) in radiata seedlings after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse

Plant part	P rate (μg P g^{-1} soil)		
	0	50	100
New shoot needles			
B / R + G[2]	0.109 a C[1]	0.139 a B	0.181 a A
B + R / G	0.122 a B	0.125 b B	0.167 b A
Old shoot needles			
B / R + G	0.060 b C	0.088 a B	0.103 a A
B + R / G	0.074 a C	0.085 a B	0.103 a A
Stem[3]			
B / R + G	0.038 b B	0.045 a B	0.064 a A
B + R / G	0.048 a B	0.044 a B	0.062 a A
Root			
B / R + G	0.040 b B	0.046 a B	0.055 a A
B + R / G	0.051 a B	0.046 a B	0.056 a A

[1]Numbers within the same column followed by the same lower case letters (plant combination) or within the same row followed by the same capital letters (P rate) for each plant part are not significantly different at $P<0.05$

[2]/ represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

[3]Statistical analysis was performed on square root ($\sqrt{Y}$) transformed data

When no P was added, P concentrations in new shoot needles, old shoot needles, stems and roots of radiata were higher (most cases significant at $P<0.05$, but all cases significant at $P<0.1$) when radiata was grown with broom compared to when radiata was grown with grass. When P was added (50 and 100 μg P g^{-1} soil), however, the P concentration in these plant organs were significantly lower or not different when radiata was grown with broom compared to radiata grown with grass. The higher plant P concentration in radiata when it was grown with broom than in the presence of grass at the zero rate of P application is probably due to significantly higher phosphatase activities in radiata rhizosphere in the presence of broom at zero P rate of application (see section 5.4.2, Chapter 5). However, this difference was not reflected in a plant-

available soil P (Bray-2 P and resin-P_i) concentration difference between the two treatments (see section 5.4.5, Chapter 5). Higher shoot needle P concentrations in the presence of broom at zero P rate of application could also be due to broom supplying more available N to radiata through N-fixation (Gadgil *et al.*, 1984; Beets and Madgwick, 1987; Li *et al.*, 2003a; Watt *et al.*, 2003c). The higher N availability to radiata might have helped radiata to take-up more P from the soil (Gillespie and Pope, 1989; Li *et al.*, 2003b). There was a slightly higher N concentration at zero P rate of application in both new and old shoot needles of radiata in the presence of broom compared to radiata in the presence of grass, though the difference was not statistically significant (Figure 6.1).

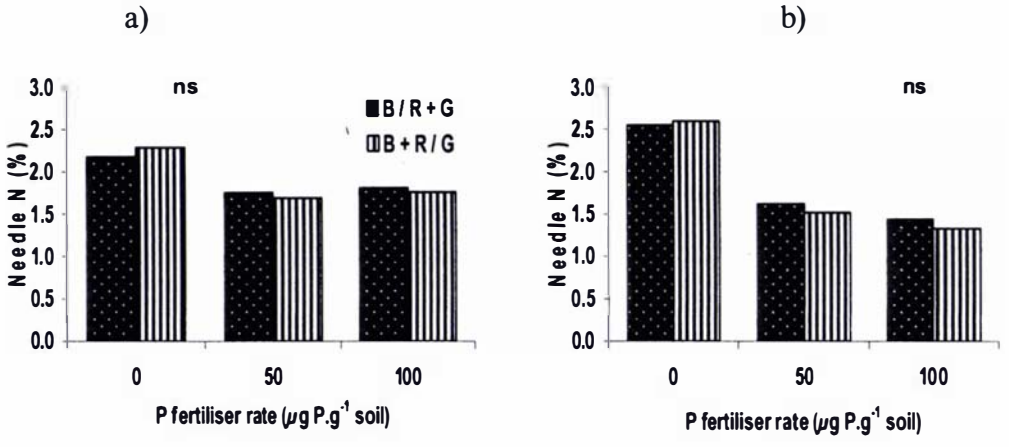

Figure 6.1 Effect of TSP fertiliser rate and plant combination on N concentration (%) in new (a) and old shoot (b) needles of radiata seedlings after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse

When P was added (50 and 100 μg P g^{-1} soil) the growth of broom increased exponentially (see section 6.4.3.2) compared to a much lower rate of grass dry matter weight increase (see section 6.4.3.3). Therefore, broom may have removed a higher proportion of the plant-available P from the soil and this may have caused a significantly lower P concentration in the new shoot needles of radiata in the presence of broom, compared to in new shoot needles in the presence of grass at these rates of P application. Such a decrease was not observed in old shoot needles, stem, and roots.

This lower P concentration in the new shoot needles when radiata was grown with broom is consistent with the Bray-2 P concentration in the rhizosphere soil of radiata in association with broom (7.3-9.8 μg P g^{-1}), which was lower than that in the rhizosphere soil of radiata in association with grass (8.2-11.3 μg P g^{-1}) for the P rates of 50 and 100 μg P g^{-1} soil (Chapter 5), indicating a higher depletion of soil plant-available P due to the higher P uptake by broom than by grass (see Table 6.6 in a later section).

6.4.1.2 Broom

Phosphorus fertiliser rate and P fertiliser rate x plant combination interaction effects on broom shoot P concentration were significant at p=0.0009 and p=0.0171, respectively (Table 6.2). But there was no effect of the treatments on broom root P concentration. The interaction effects are as a result of broom shoot P concentration being marginally higher when broom was grown alone than when it was grown with radiata at the 50 μg P g^{-1} soil rate. At 0 and 100 μg P g^{-1} soil rates there was no significant difference in shoot P concentration whether broom was grown alone or with radiata. However, the boom root and shoot dry matter yields were significantly higher when broom was grown with radiata at all P rates. Therefore, it is not clear why broom P concentration was higher when it was grown alone than when it was grown with radiata only at the 50 μg P g^{-1} soil.

As in the case of radiata, increased P fertiliser rates increased P concentrations in broom shoots whether it was grown alone or in association with radiata (Table 6.2). This is in agreement with the effect of P fertiliser rate on plant-available P in soils under broom as discussed in Chapter 5.

Table 6.2 Effect of TSP fertiliser rates on P concentration (%) in broom after 54 weeks of broom growth in an Allophanic Soil in a glasshouse

Plant part	P rate ($\mu g\ P\ g^{-1}$ soil)		
	0	50	100
Shoot			
B / R + G[1]	0.057 a B[2]	0.079 a A	0.077 a A
B + R / G	0.064 a B	0.068 b B	0.084 a A
Root			
B / R + G	0.037	0.037	0.035
B + R / G	0.041	0.034	0.038
$lsd_{(p<0.05)} = ns$			

[1]/represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)
[2]Numbers within the same column followed by the same lower case letters (plant combination) or within the same row followed by the same capital letters (P rate) are not significantly different at $P<0.05$

6.4.1.3 Ryegrass

Phosphorus fertiliser effects on shoot and root P concentrations were significant ($p=0.0002$ and $p<0.0001$, respectively). As in the case of radiata shoot, stem and roots and broom shoot, increased P fertiliser rates increased P concentrations in grass shoot and roots regardless of the plant combinations (Table 6.3). This is in agreement with the effect of P fertiliser rate on plant-available P in soils under grass (Chapter 5). There was no significant effect of plant combination or P fertiliser rate x plant combination interaction on shoot and root P concentrations.

Table 6.3 Effect of TSP fertiliser rates and plant combinations on P concentration (%) in ryegrass after 54 weeks of ryegrass growth in an Allophanic Soil in a glasshouse

Plant part	P rate (μg P g^{-1} soil)		
	0	50	100
P rate main effect			
Shoot	0.036[1] C	0.055 B	0.064 A
Root	0.042 C	0.059 B	0.071 A
P rate x plant combination interaction effect			
Shoot	0.037	0.049	0.060
B / R + G[2]	0.034	0.062	0.068
B + R / G			
lsd $_{(p<0.05)}$ = *ns*			
Root	0.042	0.060	0.071
B / R + G	0.043	0.058	0.072
B + R / G			
lsd $_{(p<0.05)}$ = *ns*			

[1]Numbers within the same row followed by the same capital letters are not different at $P<0.05$

[2]/ represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

At all rates of P application the grass shoot P concentrations were much lower than the critical P concentration of 0.3% reported for P deficiency in ryegrass (McLaren and Cameron, 1990) but it significantly increased with increased rates of P application. The low grass shoot P concentration is due to low soil P availability. The Olsen P concentrations in soils were less than 6 μg P g^{-1} soil even at the highest rate of P application (Chapter 5). This is lower than the Olsen P concentration of 20 μg P g^{-1} required to achieve near maximum growth for ryegrass (Sinclair *et al.*, 1997).

6.4.2 Relationship between plant P concentration and soil P concentration

6.4.2.1 Radiata

Phosphorus concentrations in new and old shoot needles were regressed against different soil P tests (Bray-2 P, NaOH-P_i fraction, and resin-P_i fraction in rhizosphere soils and resin-P_i *in situ* in bulk soil) (Figures 6.2 and 6.3). The regression analysis showed that the data fit best to logarithmic equations. Therefore logarithmic relationships were obtained for all the above regressions.

Phosphorus concentration in the new and old shoot needles had significant logarithmic relationships with Bray-2 P concentration in the soil whether the radiata seedlings were grown with ryegrass or with broom (new shoot needles: $R^2 = 0.64$, $P=0.0019$ for radiata + grass; $R^2 = 0.53$, $P=0.0070$ for radiata + broom, and old shoot needles: $R^2 = 0.83$, $P<0.0001$ for radiata + grass; $R^2 = 0.79$ $P=0.0001$ for radiata + broom) (Figures 6.2 and 6.3).

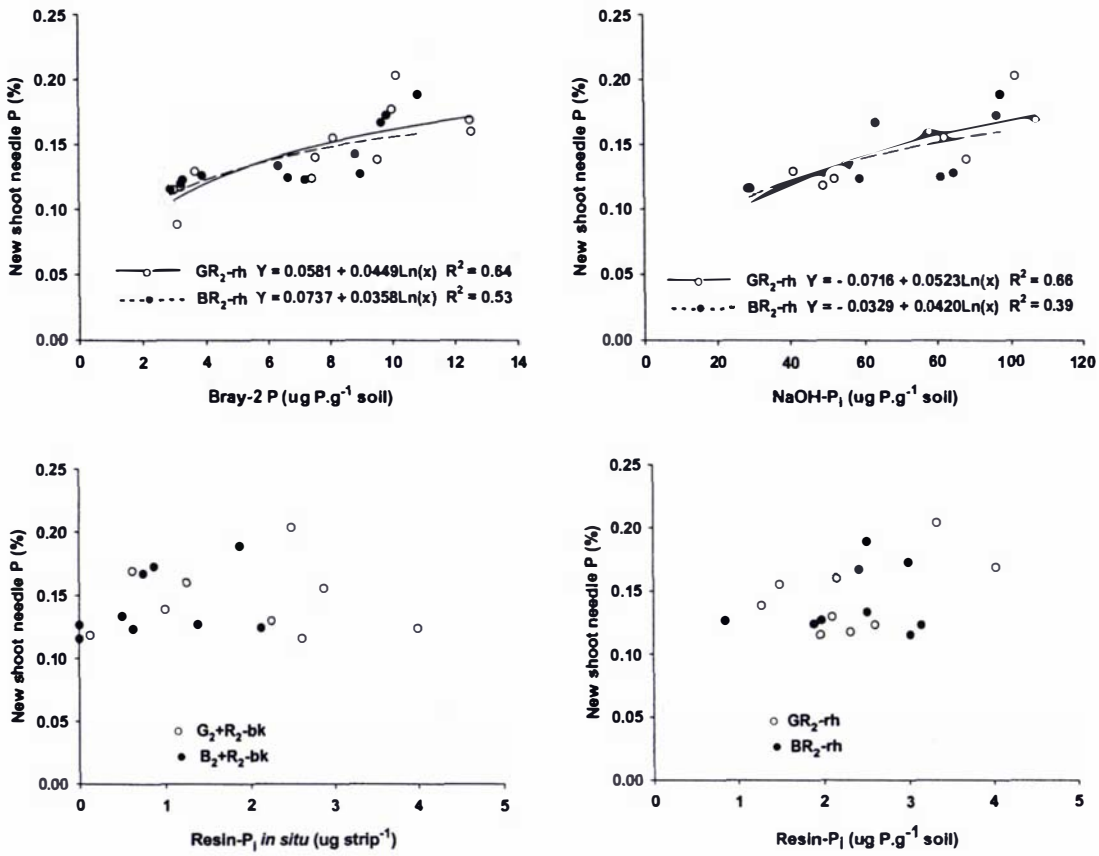

Figure 6.2 Relationship between new shoot needle P concentration of radiata seedlings and P extracted by different plant-available soil P tests after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse (Bray-2 P, resin-P_i and NaOH-P_i concentration from the rhizosphere soil, and resin-P_i *in situ* from the bulk soil). GR_2-rh – rhizosphere soil from radiata grown with grass. BR_2-rh – rhizosphere soil from radiata grown with broom. G_2+R_2-bk – bulk soil from radiata grown with grass. B_2+R_2-bk – bulk soil from radiata grown with broom.

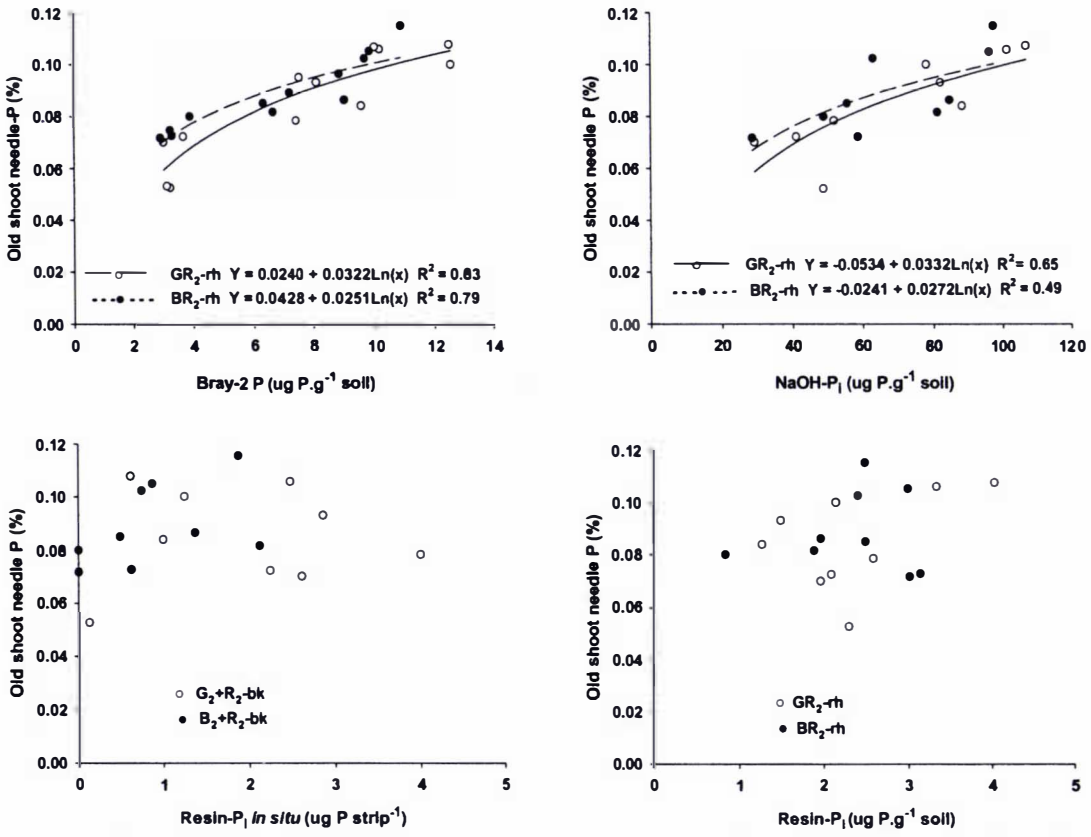

Figure 6.3 Relationship between old shoot needle P concentration of radiata seedlings and P extracted by different plant-available soil P tests after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse (Bray-2 P, resin-P_i and NaOH-P_i concentration from the rhizosphere soil, and resin-P_i *in situ* from the bulk soil). GR_2-rh – rhizosphere soil from radiata grown with grass. BR_2-rh – rhizosphere soil from radiata grown with broom. G_2+R_2-bk – bulk soil from radiata grown with grass. B_2+R_2-bk – bulk soil from radiata grown with broom.

Phosphorus concentration in the new shoot needles also had a significant logarithmic relationship with NaOH-P_i concentrations in the soils when radiata seedlings were grown with ryegrass, but not when they were grown with broom (R^2 = 0.66, P=0.0075 for radiata + grass; R^2 = 0.39, P=0.074 for radiata + broom) (Figure 6.2). In the old shoot needles, however, P concentration had a significant logarithmic relationship with NaOH-P_i concentration under both plant combinations (R^2 = 0.65, P=0.0083 for radiata + grass; R^2 = 0.49, P=0.0366 for radiata + broom) (Figure 6.3). The curvilinear

relationships of needle P concentrations with Bray-2 P and NaOH-P_i concentrations suggest 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. Meanwhile, new and old shoot needle P concentrations had no significant relationship with resin-P_i concentration.

The above results suggest that Bray-2 P is a better soil test to predict soil P availability to radiata seedlings than the resin-P_i soil test. Bray-2 P is strongly correlated with the NaOH-P_i concentration (R^2 = 0.92) (Chapter 5), which is characterized by P adsorbed to allophane and Fe+Al oxides. These results suggest that the radiata seedlings were taking up P from the NaOH-P_i pool in addition to the more labile resin-P_i pool. The extremely low resin-P_i (1-5 μg P g^{-1} soil) pool in the soils (Figure 6.2) was probably unable to supply all the P needs of the seedlings (P uptake by radiata + grass or by radiata + broom was 5-50 μg P g^{-1} soil, Table 6.6).

6.4.2.2 Broom

When broom shoot P concentration was regressed against different soil P tests (Bray-2 P, NaOH-P_i fraction, resin-P_i *in situ*, and resin-P_i fraction), it had a highly significant logarithmic relationship with Bray-2 P when broom was grown alone (compartment 1) (R^2 = 0.62, P=0.0025) and a marginally significant linear relationship when broom was grown with radiata (R^2 = 0.34, P=0.0487) (compartment 2) (Figure 6.4). It had no relationship with the other three soil tests.

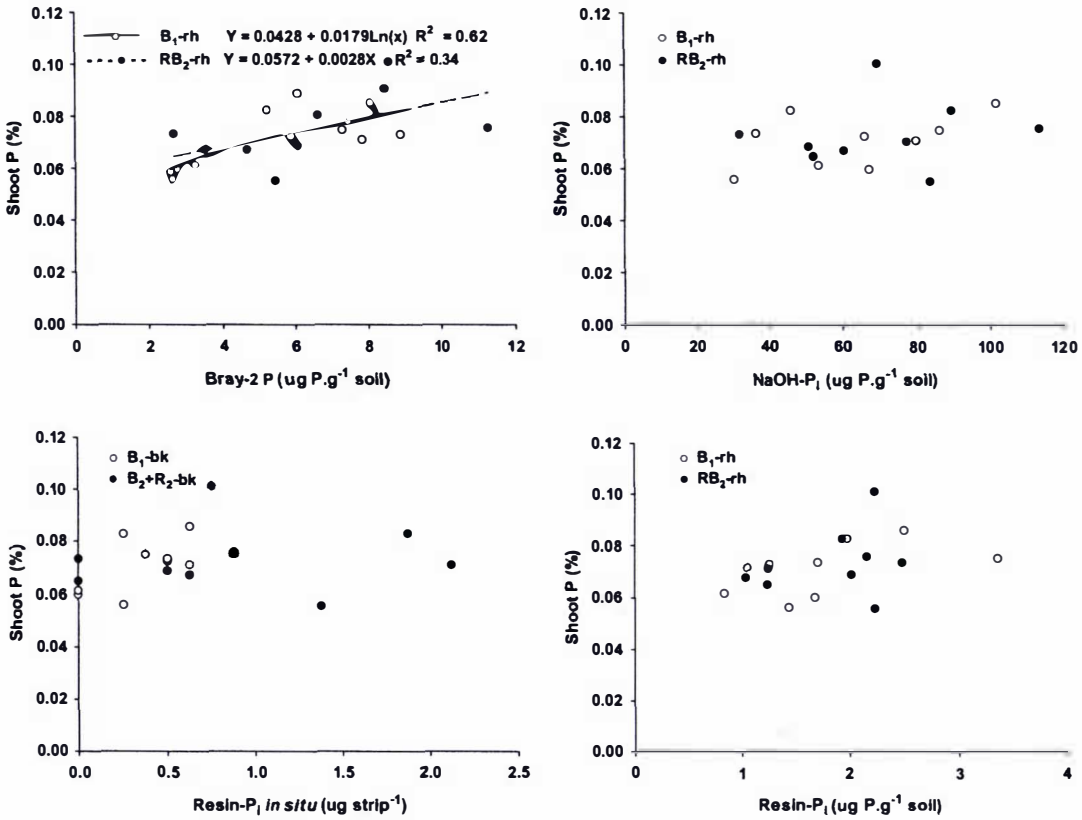

Figure 6.4 Relationship between broom shoot P concentration and P extracted by different plant-available soil P tests after 54 weeks of broom growth in an Allophanic Soil in a glasshouse (Bray-2 P, NaOH-P_i, and resin-P_i concentration from the rhizosphere soil, and resin-P_i *in situ* from the bulk soil). B_1-rh – rhizosphere soil from broom alone. RB_2-rh – rhizosphere soil from broom grown with radiata. B_1-bk – bulk soil from broom alone. B_2+R_2-bk – bulk soil from broom grown with radiata.

Bray-2 P extracts P associated with Fe, Al and Ca (Mehlich, 1978). The fact that broom shoot P concentration is related to Bray-2 P indicates that broom is taking up P from one or more of these P pools. However, the shoot P concentration was not related to NaOH-P_i concentration (Fe, Al bound P) whether broom was grown alone or with radiata, unlike in the case with radiata (section 6.4.2.1). The absence of any relationship between shoot P concentration and NaOH-P_i could be due to a much larger broom yield when P was applied especially at the rate of 100 μg P g^{-1} soil (Table 6.5), which would

have had a dilution effect on shoot P concentration. This is supported by the data on P uptake by broom which is discussed later in section 6.4.3.1. However, in spite of this dilution effect Bray-2 P concentration had a significant relationship with shoot P concentration.

6.4.2.3 Ryegrass

The grass shoot P concentration had significant logarithmic relationships with Bray-2 P, NaOH-P_i and resin-P_i concentrations in the rhizosphere soils whether the grass was grown alone (compartment 1) (R^2 = 0.64, P=0.0018; R^2 = 0.45, P=0.0476; R^2 = 0.51, P=0.0307, respectively) or the grass was grown with radiata (compartment 2) (R^2 = 0.72, P=0.0005, R^2 = 0.68, P=0.0064, R^2 = 0.52, P=0.0290, respectively) (Figure 6.5).

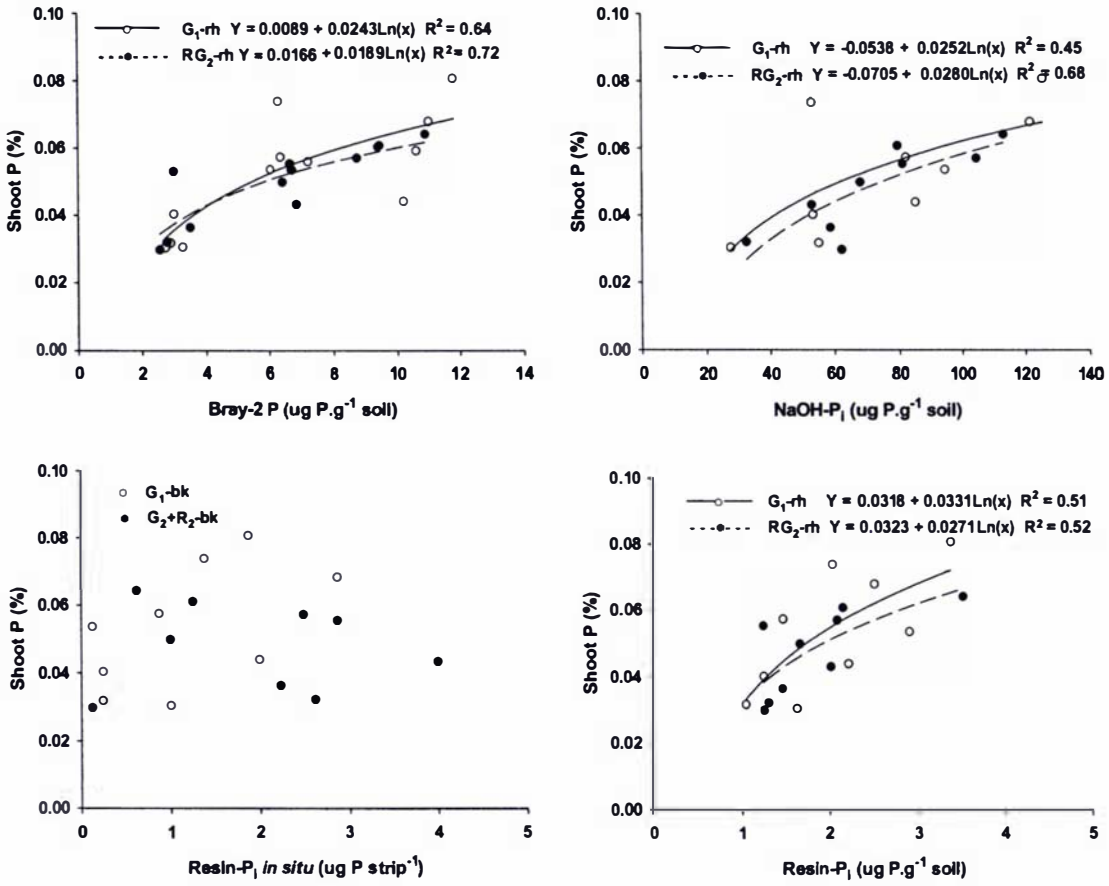

Figure 6.5 Relationship between ryegrass shoot P concentration and P extracted by different plant-available soil P tests after 42 weeks of ryegrass growth in an Allophanic Soil in a glasshouse (Bray-2 P, NaOH-P_i, and resin-P_i concentration from the rhizosphere soil, and resin-P_i *in situ* from the bulk soil). G_1-rh – rhizosphere soil from grass alone. RG_2-rh – rhizosphere soil from grass grown with radiata. G_1-bk – bulk soil from broom alone. G_2+R_2-bk – bulk soil from broom grown with radiata.

The higher R^2 values for the relationship between grass shoot P concentration with Bray-2 P and NaOH-P_i concentrations when grass was grown with radiata compared with when grass was grown alone, is likely to be an indication that there was an influence of radiata rhizosphere processes inducing P availability to the grass from the Bray-2 P and NaOH-P_i pools. In Chapter 5 it has been shown that radiata roots induced acidification and increased acid phosphatase activity in the grass rhizosphere soil. These

root induced effects increased Bray-2 P concentration in the grass rhizosphere soil probably by mobilising NaOH-P_i and NaOH-P_o resulting in increased shoot P concentration.

6.4.3 Plant growth

6.4.3.1 Radiata

At the end of 54 weeks of radiata growth, there was a significant ($p<0.0001$) response of radiata shoot, root and total (shoot + root) dry matter yield to P fertiliser rates. There was also significant ($p<0.05$) interactions of P fertiliser rates and plant combinations on root and total dry matter yields but not on shoot dry matter yield.

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 6.4). There was however no significant difference in any of these yields between 50 and 100 μg P g^{-1} soil treatments. The highly significant effects of P fertiliser rate on these dry matter weights are not surprising as the native soil had a very low plant-available P concentration (Chapter 5). These results are consistent with the increase of P concentration in both new and old shoot needles with the increased rates of P application (Table 6.1, section 6.4.1).

The interaction effects of P fertiliser rate and plant combination on total dry matter and root dry matter were demonstrated by the significant difference in these yields at the P fertiliser rate of 100 μg P g^{-1} soil between radiata grown with broom and radiata grown with grass, but not at the P fertiliser rates of 0 and 50 μg P g^{-1} soil (Table 6.4).

Table 6.4 Effect of TSP fertiliser rates and plant combinations on shoot, root and total dry matter weights (g pot^{-1}) of radiata seedlings after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse

Plant part	P rate (μg P g^{-1} soil)		
	0	50	100
P rate main effect			
Shoot	10.5[1] B	62.6 A	66.0 A
Root[2]	2.6 B	18.0 A	20.0 A
Total[3]	13.1 B	80.6 A	86.0 A
P rate x plant combination interaction effect			
Shoot			
B / R + G[4]	9.9	62.6	72.6
B + R / G	11.1	62.5	59.3
$lsd_{(p<0.05)} = ns$			
Root[2]			
B / R + G	2.3 a B	17.2 a A	23.6 a A
B + R / G	2.9 a B	18.8 a A	16.4 b A
Total[3]			
B / R + G	12.2 a B	79.8 a A	96.3 a A
B + R / G	14.0 a B	81.4 a A	75.6 b A

[1]Numbers within the same row followed by the same capital letters (P rate) or within the same column followed by the same lower case letters (plant combination) for each plant part are not significantly different at $P<0.05$
[2]Statistical analysis was performed on $\log_e$ (Y) transformed data
[3]Statistical analysis was performed on square root ($\sqrt{Y}$) transformed data
[4]/ represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

The higher total dry matter yield of radiata when it was in association with grass compared to when it was in association with broom at the application rate of 100 μg P g^{-1} soil is probably due to the competition for P and other nutrients between radiata and broom, as a result of the markedly higher broom dry matter yield at this P rate compared

to the grass dry matter yield when they were grown with radiata (see next two sections, Table 6.5 and 6.7). The much higher root density of broom in the soil compared to that of grass when these plants were in association with radiata at the P rate of 100 μg P g^{-1} soil support this competition explanation.

The needle P concentrations in new shoots were significantly lower (0.167%) when radiata was in association with broom than when radiata was in association with grass (0.181%) at the P rate of 100 μg P g^{-1} soil (Table 6.1). This suggests that there was competition between broom and radiata for P at this high rate of P application. It is also possible that the reduction in radiata yield when radiata was grown with broom could be due to the competition for other nutrients. When P fertiliser was applied, the radiata needle N concentration was slightly lower in the presence of broom than in the presence of grass (Figure 6.1). Therefore there might have been competition for N between broom and radiata even though broom was fixing atmospheric N. The N-fixed was probably not sufficient to meet the N needs of the vigorously growing broom. Using ^{15}N isotopic studies, Watt *et al.* (2003c) also reported that there was competition for N when broom was grown with radiata in a forest located near Hororata, Christchurch.

In the 0 and 50 μg P g^{-1} soil treatments, broom root and shoot dry matter yields were much lower than in the 100 μg P g^{-1} (see Table 6.5 in later section) and, therefore, the competition for nutrients other than P between radiata and broom is expected to be low, if any. Without P fertiliser addition (0 μg P g^{-1} soil), although the new shoot needle P concentration was marginally in the deficiency class, it was not significantly different between radiata in association with grass and with broom (see Table 6.1). However, at 50 μg P g^{-1} soil when radiata was grown with broom, the P concentration in the new shoot needles (0.125%) was significantly lower than that when radiata was grown with grass (0.139%), but this difference did not reflect in radiata yield difference between the two plant associations.

Scott (2002) compared the dry matter yield of radiata seedlings, radiata seedlings grown with lucerne (a legume like broom), radiata seedlings grown with ryegrass, lucerne grown alone, and ryegrass grown alone in pots containing Immature Pallic Soils having four soil fertility levels with respect to total P and organic carbon, namely low P and

low C (320 $\mu g\ g^{-1}$; 2.5%), low P and high C (524 $\mu g\ g^{-1}$; 5.1%), high P and high C (768 $\mu g\ g^{-1}$; 4.0%), and high P and low C (721 $\mu g\ g^{-1}$; 2.4%). He reported that when radiata seedlings were grown with lucerne, the dry matter yield of radiata seedlings tended to decrease with increased soil P fertility status, while the dry matter of lucerne tended to increase, as observed in the present study with broom, when it was grown with radiata. Meanwhile, the dry matter of radiata and grass in Scott's study did not show any difference when they were grown together compared to when they were grown separately at all soil P fertility levels. This was consistent with the P concentrations in the respective plants. When radiata was grown with lucerne, the P concentration in radiata remained the same with increased soil P fertility status, while P concentration in lucerne increased with increased soil P fertility status. Meanwhile, when radiata or lucerne was grown alone, the P concentration in the plants consistently increased with increased soil P fertility status, suggesting that there might have been competition for P between radiata and lucerne when they were grown together in the high P fertility status soil.

When the data of radiata shoot dry matter was related with the data of P concentration in new and old shoots (Figure 6.6), it showed two lumps (shoot dry matter 5-15 and 45-80 g pot^{-1}) with no yield data between 15 and 45 g pot^{-1}. Meanwhile, the total dry matter of radiata also showed two lumps (total dry matter 15-20 and 60-100 g pot^{-1}) with no yield data between 20 and 60 g pot^{-1} (Figures 6.7). Therefore, no attempts were made to determine the relationship between radiata shoot dry matter and shoot needle and between total dry matter and P extracted by different soil P tests (Bray-2 P, NaOH-P_i, and resin-P_i). In addition, needle P concentration were higher than the critical P concentration showing that P was not limiting yield and therefore growth equation such as Mitscherlich-type equation can not be used to describe the relationship.

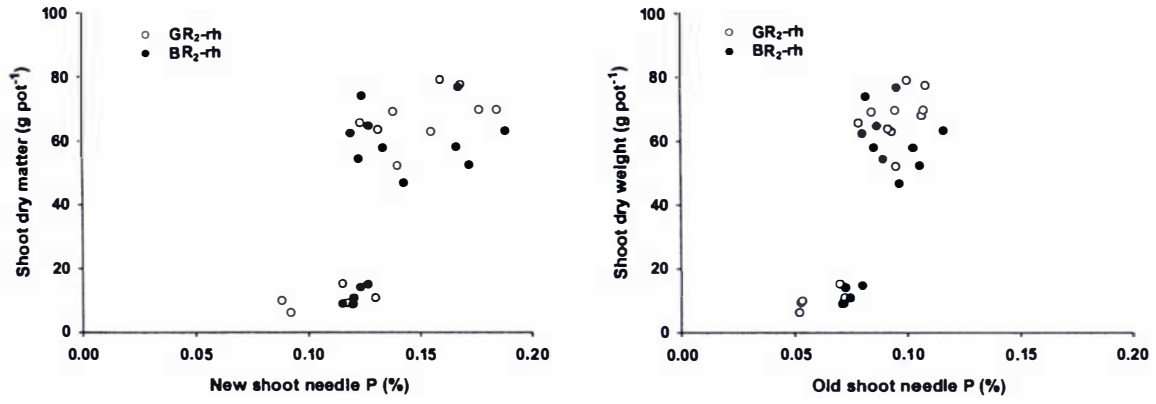

Figure 6.6 Relationship between radiata shoot yield and new and old shoot needle P concentration of radiata seedlings after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse. GR_2-rh – rhizosphere soil from radiata grown with grass. BR_2-rh – rhizosphere soil from radiata grown with broom.

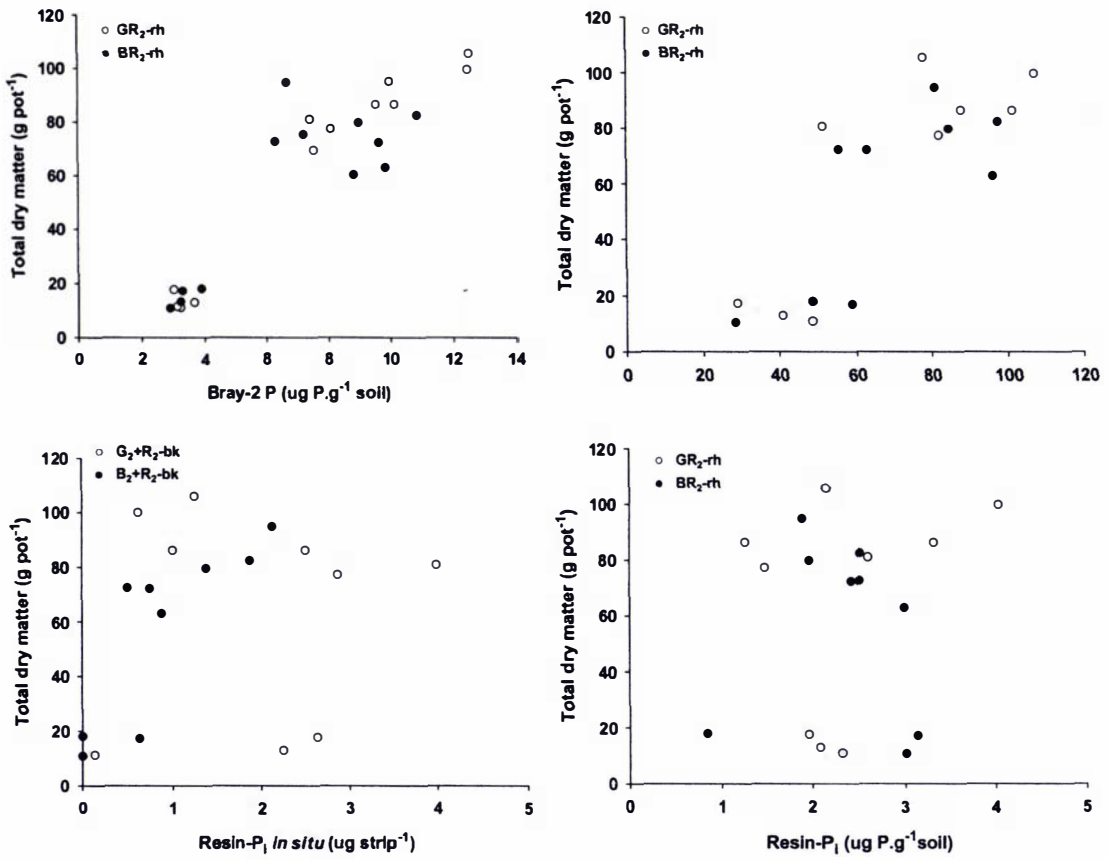

Figure 6.7 Relationship between total dry matter yield of radiata seedlings and P extracted by different soil P tests after 54 weeks of radiata growth in an Allophanic Soil in a glasshouse trial (Bray-2 P, NaOH-P_i, and resin-P_i concentration from the rhizosphere soils, resin-P_i *in situ* from the bulk soils). GR_2-rh – rhizosphere soil from radiata grown with grass. BR_2-rh – rhizosphere soil from radiata grown with broom. G_2+R_2-bk – bulk soil from radiata grown with grass. B_2+R_2-bk – bulk soil from radiata grown with broom.

6.4.3.2 Broom

There were significant ($p<0.0001$) broom shoot, root and total dry matter weight responses to increasing P rates. Plant combination also had significant effects on broom shoot, root and total dry matter weights ($p<0.0001$; $p<0.0001$; $p<0.0001$, respectively). There was a significant ($p=0.0019$) interaction effect between P fertiliser rate and plant combination on broom root dry matter production but not on broom shoot and total dry

matter production. This interaction effect is most likely due to the differences in soil volumes used for growing broom alone in compartment 1 of the tray (1 kg soil) and broom plus radiata in compartment 2 of the tray (2 kg soil) (Chapter 5, Figure 5.1).

Shoot, root and total dry matter of broom increased approximately two fold to the addition of 50 μg P g^{-1} soil and five fold to the addition of 100 μg P g^{-1} soil, compared with the control treatment (0 μg P g^{-1} soil) (Table 6.5). These results are consistent with the increase of broom shoot P concentration with increased P fertiliser rates of addition (Table 6.2, section 6.4.1).

Table 6.5 Effect of TSP fertiliser rates on shoot, root, and total dry matter yields (g pot^{-1}) of broom after 54 weeks of broom growth in an Allophanic Soil in a glasshouse

Plant part	P rate (μg P g^{-1} soil)			
	0	50	100	Mean
P rate main effect				
Shoot[2]	4.1 C[1]	9.6 B	22.3 A	
Root[2]	4.0 C	8.9 B	19.2 A	
Total[2]	8.0 C	18.5 B	41.5 A	
P rate x plant combination interaction effect				
Shoot[2]				
B / R + G[3]	3.0	7.9	15.7	**8.8 b**
B + R / G	5.2	11.3	29.0	**15.1 a**
Root[2]				
B / R + G	3.4 b C	7.2 b B	12.4 b A	
B + R / G	4.5 a C	10.7 a B	26.0 a A	
Total[2]				
B / R + G	6.4	15.0	28.1	**16.5 b**
B + R / G	9.7	22.0	55.0	**28.9 a**

[1]Numbers within the same row followed by the same capital letters (P rate) or within the same column followed by the same lower case letters (plant combination) for each plant part are not significantly different at $P<0.05$

[2]Statistical analysis was performed on $\log_e$ (Y) transformed data

[3]/ represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

When broom was grown with radiata, the shoot, root and total broom dry matter weights were much higher than the corresponding weights of broom when it was grown alone at all P rates (compartment 1) (Table 6.5). This is probably due to the higher soil volume used for growing broom with radiata than when broom was grown alone. The soil volume when broom was grown with radiata was twice that of when broom was grown alone. This resulted in higher broom root dry matter weight when broom was grown with radiata. Therefore, more soil volume was explored by roots for nutrient uptake. At 100 μg P g^{-1} soil treatment, the broom root dry weight when broom was grown with radiata was more than double compared with when it was grown alone. At 50 μg P g^{-1} soil treatment it was 50% more and at 0 μg P g^{-1} soil treatment it was 30% more.

The relationship of broom dry matter weight and soil P test data did not fit to a Mitscherlich-type equation as observed for radiata dry weight but fitted to an exponential equation. The total broom dry matter weight showed a significant exponential relationship with Bray-2 P concentration in the broom rhizosphere soils, when broom was grown alone ($R^2 = 0.86$; $P<0.0001$), as well as when broom was grown with radiata ($R^2 = 0.84$; $P<0.0001$) (Figure 6.8). The data show that for a fixed Bray-2 P concentration, broom grown in association with radiata had a higher dry matter yield than broom grown alone. The P uptake by broom was also higher when broom was grown with radiata compared to when broom was grown alone for each of the P treatment (Table 6.6). These differences are due to the differences in soil volumes used for growing broom alone and broom + radiata as discussed earlier in this section.

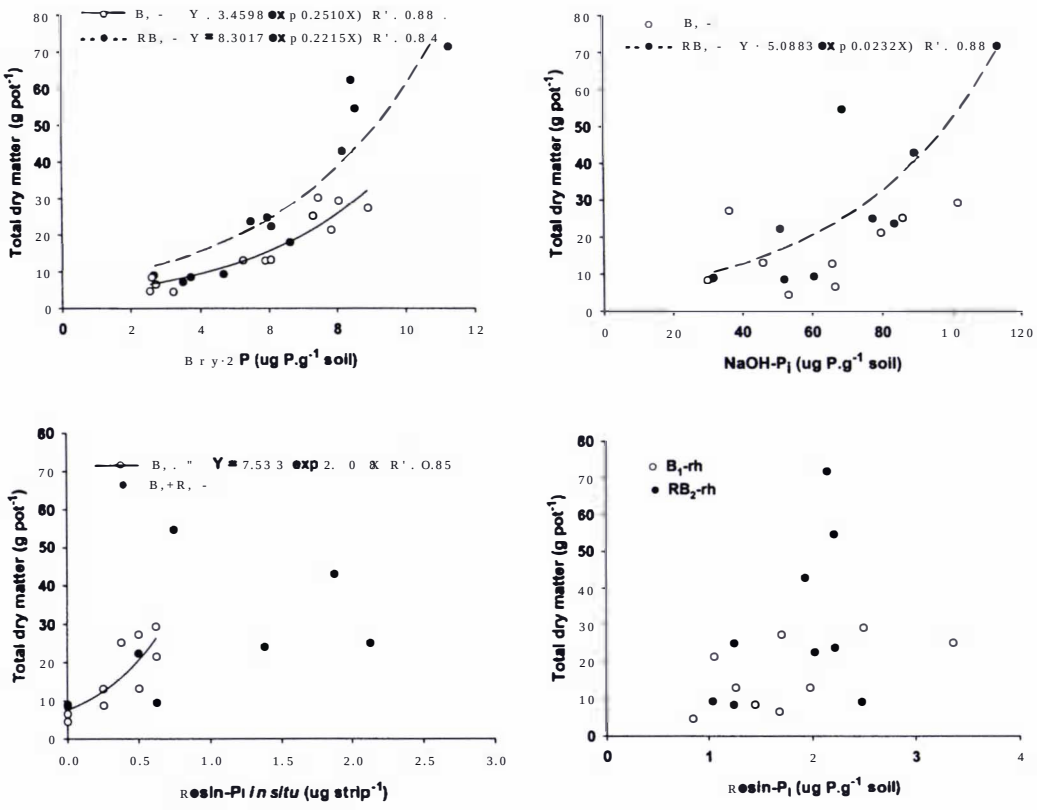

Figure 6.8 Relationship between total broom dry matter and P extracted by different soil P tests after 54 weeks of broom growth in an Allophanic Soil in a glasshouse (Bray-2 P, NaOH-P_i, and resin-P_i concentrations from the rhizosphere soil, and resin-P_i *in situ* from the bulk soil). B_1-rh – rhizosphere soil from broom alone. RB_2-rh –rhizosphere soil from broom grown with radiata. B_1-bk – bulk soil from broom alone. B_2+R_2-bk – bulk soil from broom grown with radiata.

Table 6.6 Phosphorus uptake by radiata, broom and ryegrass (mg P pot^{-1}) for each TSP rate and plant combination after 54 weeks of radiata and broom growth and 42 weeks of ryegrass growth in an Allophanic Soil in a glasshouse

P rate (μg P g^{-1})	Plant combination	Plant species		
		Radiata	Broom	Ryegrass
0	B / R + G*	6.7	3.0	2.8
	B + R / G	9.3	5.2	1.0
50	B / R + G	54.2	8.7	4.2
	B + R / G	52.8	11.5	3.1
100	B / R + G	78.3	16.9	5.5
	B + R / G	61.9	34.7	4.7

*/represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

The exponential relationships obtained for broom as opposed to the logarithmic relationships obtained for radiata (section 6.4.3.1) and grass (see next section) probably suggests that broom has a higher external efficiency of P utilisation at the higher rate of P application. The broom root weight doubled when P rate increased from 50 to 100 μg P g^{-1} soil whereas the radiata and grass root weights (Tables 6.4 and 6.7) did not change. This increase in broom root weight is due to increased N fixation by broom at increased P availability in the soils.

When broom was grown with radiata, there was a significant relationship between total broom dry matter yield and NaOH-P_i concentration (R^2 = 0.68; P=0.0064), while when broom was grown alone there was no such relationship (R^2 = 0.31; P=0.1175) (Figure 6.8). Meanwhile, resin-P_i *in situ* concentrations had a significant (R^2 = 0.65; P=0.0087) relationship with total dry matter yield only when broom was grown alone. This tends to suggest that when broom was grown alone it took up P mainly in proportion to the

smaller resin-P_i pool but when it was grown with radiata, it took up P in proportion to P mobilised by radiata roots from the much larger NaOH-P_i pool. The significant (R^2 = 0.52; P=0.0273) relationship between P uptake by broom when it was grown with radiata and NaOH-P_i concentrations in the soil is consistent with this suggestion (Figure 6.9).

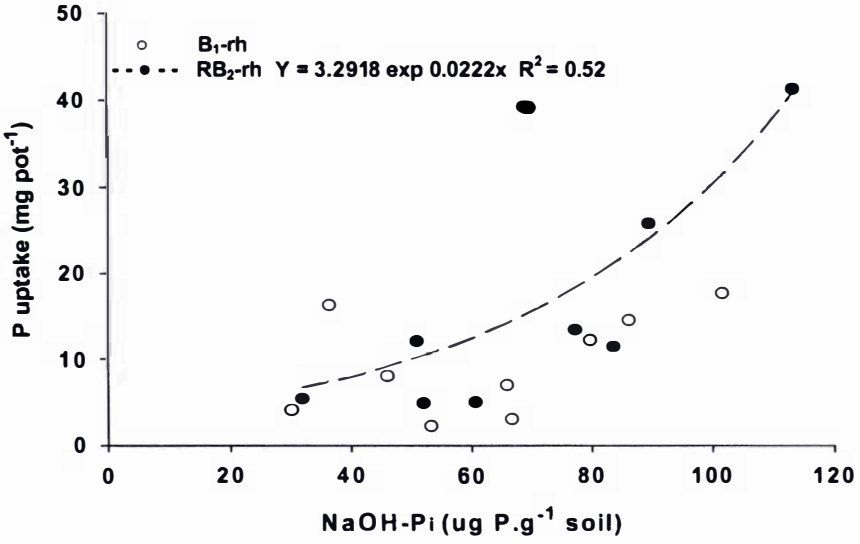

Figure 6.9 Relationship between P uptake by broom and NaOH-P_i concentration in the rhizosphere soil after 54 weeks of broom growth in an Allophanic Soil in a glasshouse. B_1-rh – rhizosphere soil from broom alone. RB_2-rh – rhizosphere soil from broom grown with radiata.

6.4.3.3 Ryegrass

Total and root dry matter yields of grass were much lower than those of radiata and broom for all rates of P application. The phosphorus fertiliser rate had a significant effect on grass total and root dry matter production (p=0.0013 for total; p<0.0001 for root) (Table 6.7). Plant combination also had a significant effect on total dry matter yield (p=0.0045) and root dry matter yield (p=0.0005), as in the case of broom, but had no effect on shoot dry matter yield. The interaction between P fertiliser rates and plant

combinations had a significant effect on shoot dry matter weight (p=0.0214) but not on total dry matter and root dry matter weight.

As reported earlier under the section on broom (section 6.4.3.1), the soil weight used for growing grass alone in compartment 1 of the tray (1 kg soil) was half of that used for growing grass plus radiata in compartment 2 of the tray (2 kg soil) (Chapter 5, Figure 5.1). Therefore, this significant plant combination effect on grass shoot dry matter weight is most likely due to the differences in soil weight used instead of the differences in plant combinations (grass alone versus grass + radiata).

Table 6.7 Effect of TSP fertiliser rates on shoot, root, and total dry matter yield (g pot^{-1}) of ryegrass after 42 weeks of ryegrass growth in an Allophanic Soil in a glasshouse

Plant part	P rate (μg P g^{-1} soil)			
	0	50	100	Mean
P rate main effect				
Shoot	2.8	3.0	4.0	
lsd $_{(p<0.05)}$ =*ns*				
Root	2.1 B[1]	3.8 A	4.2 A	
Total	4.9 C	6.8 B	8.2 A	
P rate x plant combination interaction effect				
Shoot				
B / R + G[2]	4.1 a A	3.0 a A	3.8 a A	
B + R / G	1.4 b B	3.0 a A	4.1 a A	
Root				
B / R + G	3.1	4.8	4.8	**4.2 a**
B + R / G	1.2	2.9	3.7	**2.6 b**
Total				
B / R + G	7.2	7.8	8.6	**7.9 a**
B + R / G	2.6	5.8	7.8	**5.4 b**

[1]Numbers within the same row followed by the same capital letters (P rate) or within the same column followed by the same lower case letters (plant combination) for each plant part are not significantly different at P<0.05

[2]/represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

Increased rates of P fertiliser addition significantly increased the grass total, shoot and root dry matter yields when grass was grown alone (Table 6.7) as observed for radiata (Table 6.4) and broom (Table 6.5) yields. This is consistent with the increase in grass shoot P concentration with increased P fertiliser rates of addition (Table 6.3, section 6.4.1.3). However, when grass was grown with radiata the grass shoot yield has not increased with increased rates of P fertiliser (Table 6.7). This is probably due to nutrients other than P limiting grass yield at high rates of P addition as a result of competition from radiata. The grass shoot N concentrations were much lower than the critical shoot N concentration of 4% (Mackay *et al.*, 1995) and decreased with increased rates of P fertiliser addition (Table 6.8). When no P was added, grass shoot yield when grass was grown with radiata was thrice that of when grass was grown alone. This is because of double the soil volume used for growing grass with radiata than grass alone. Also, at the zero P addition rate the yield of radiata was much lower than at high P rates and, therefore, competition of radiata for nutrients was much lower, if there was any at the zero P addition rate.

Table 6.8 Effect of TSP fertiliser rates on N concentration (%) in ryegrass shoots after 42 weeks of ryegrass growth in an Allophanic Soil in a glasshouse

Plant part	P rate (μg P g^{-1} soil)		
	0	50	100
P rate main effect			
Shoot	2.72 A[1]	0.79 B	0.57 B
P rate x plant combination interaction effect			
Shoot			
B / R + G[2]	2.42	0.79	0.53
B + R / G	3.03	0.79	0.60
$lsd_{(p<0.05)} = ns$			

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

[2]/ represents nylon mesh separating the plants between compartments 1 and 2 in trays (see Figure 5.1, Chapter 5)

When grass was grown alone, Mitscherlich equations showed the best fit for grass total dry matter yield to the Bray-2 P and NaOH-P_i concentrations (R^2 = 0.74; P=0.0023; R^2 = 0.75; P=0.0153, respectively) (Figure 6.10). But grass yield was not related to any of the soil P tests when grass was grown with radiata. However, grass P concentration (Figure 6.5) and grass P uptake (Figure 6.11) were significantly related to Bray-2 P and NaOH-P_i concentrations in grass rhizosphere soils when grass was grown with radiata.

The absence of any relationship between ryegrass yield and Bray-2 P and NaOH-P_i concentrations when ryegrass was grown with radiata is because, unlike Bray-2 P and NaOH-P_i concentrations, the ryegrass yield did not change with P fertiliser additions. The reason for ryegrass yield not increasing with increased P rates of addition when it was grown with radiata was explained earlier in this section as the grass yield at high soil P levels was affected by a deficiency of nutrients other than P as a result of competition between radiata and grass. When ryegrass was grown alone, however, the ryegrass yield was significantly lower than when it was grown with radiata, when no P fertiliser was added. This is probably because half the volume of soil was used for its growth compared to when it was grown with radiata. Under this condition P may have been more limited than other nutrients when no P fertiliser was added and, therefore, the grass yield would have increased with an increase in Bray-2 P and NaOH-P_i concentrations.

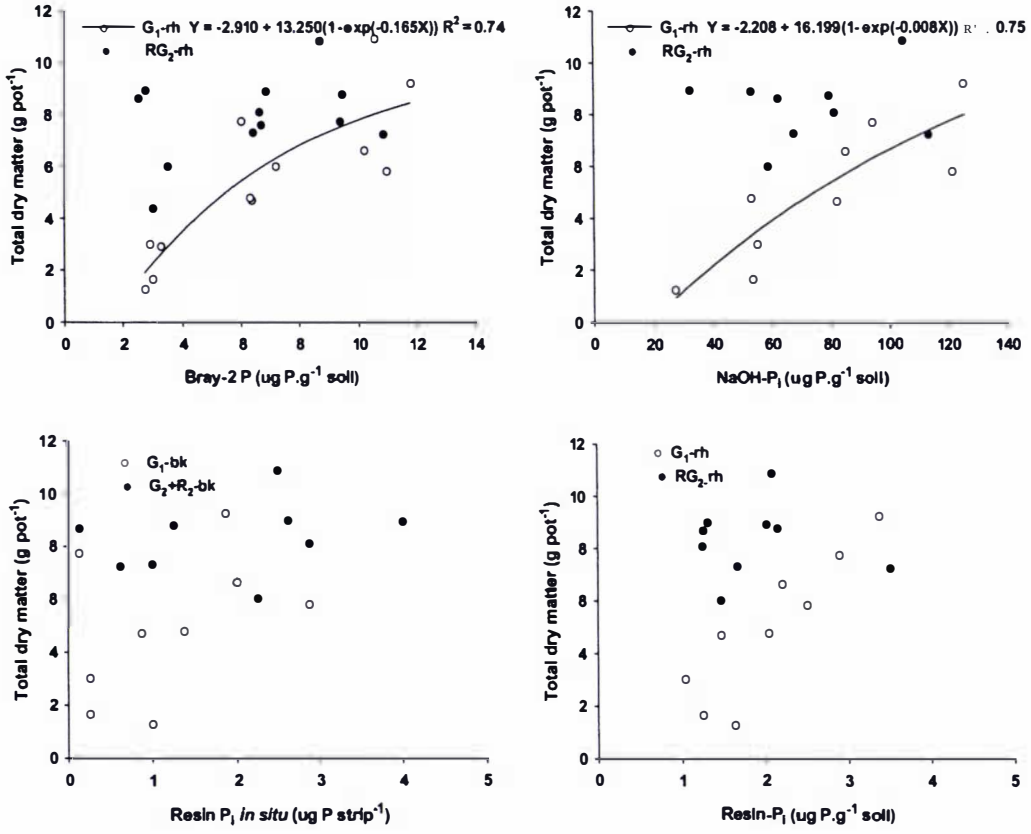

Figure 6.10 Relationship between total ryegrass dry matter and P extracted by different plant-available soil P tests after 42 weeks of ryegrass growth in an Allophanic Soil in a glasshouse (Bray-2 P, NaOH-P_i, and resin-P_i concentration from rhizosphere soil, except resin-P_i *in situ* from bulk soil). G_1-rh – rhizosphere soil from grass alone. RG_2-rh – rhizosphere soil from grass grown with radiata. G_1-bk -bulk soil from broom alone. G_2+R_2-bk – bulk soil from broom grown with radiata.

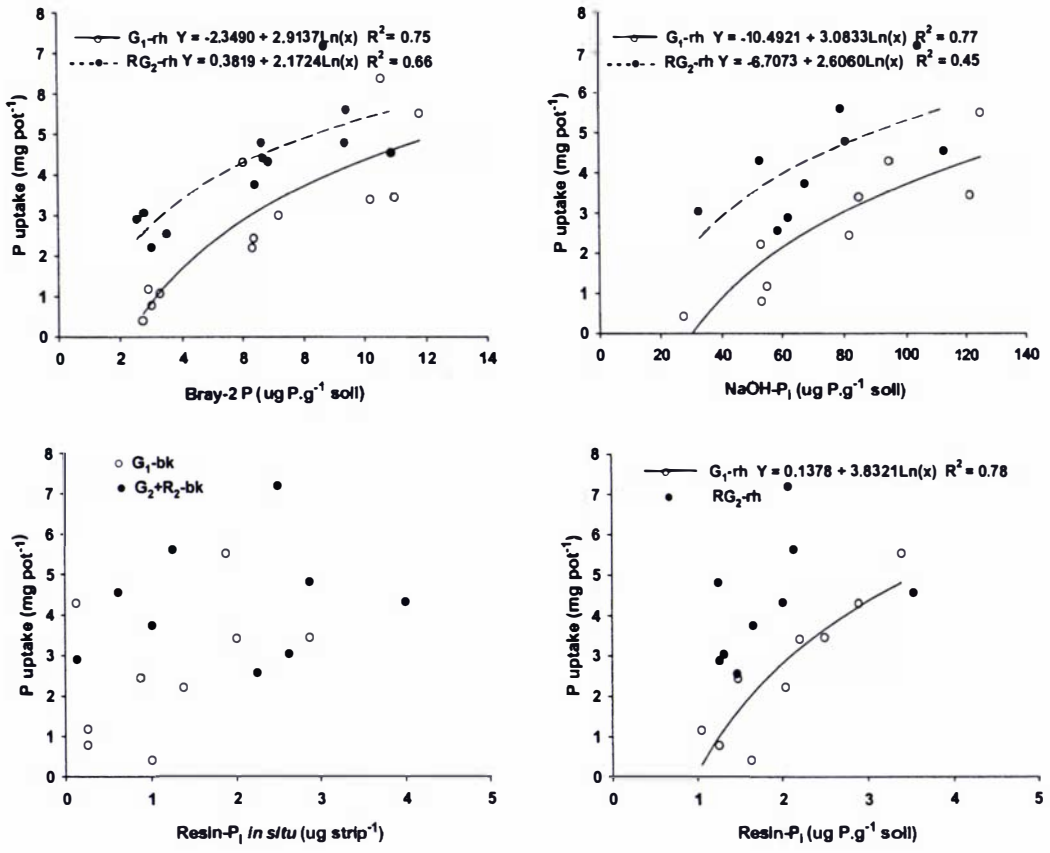

Figure 6.11 Relationship between P uptake by ryegrass and P extracted by different plant-available soil P tests after 42 weeks of ryegrass growth in an Allophanic Soil in a glasshouse (Bray-2 P, NaOH-P_i, and resin-P_i concentration from rhizosphere soil, except resin-P_i *in situ* from bulk soil). G_1-rh – rhizosphere soil from grass alone. RG_2-rh – rhizosphere soil from grass grown with radiata. G_1-bk – bulk soil from broom alone. G_2+R_2-bk – bulk soil from broom grown with radiata.

6.4.4 Recovery of fertiliser P in soil and plants

Between 85-100% of P added in fertiliser was recovered in either soil or plants. Of this, 46-49% of added P was recovered in the NaOH-P_i pool in the soil and 30-35% in the plants (Table 6.9). The highest recovery in soil was in the NaOH-P_i pool because of the high P fixing capacity of the soil. The high fertiliser P recovery in plants is at the high end of the 5 to 30% fertiliser P recovery range usually found in plants (McLaughlin *et*

al., 1988). The high recovery of fertiliser P in plant tissue is because the soil used in the study was highly P deficient (Bray-2 P 3 μg P g^{-1}) and, therefore, the plants had to take up P mainly derived from the fertiliser. The fertiliser P recovery was highest in radiata and lowest in ryegrass (see Table 6.6).

Table 6.9 The % recovery of added fertiliser P in an Allophanic Soil (P fractions)[1] and plants after 54 weeks of plant growth in a glasshouse

	Bulk soil P fertiliser rate (μg P g^{-1} soil)		Rhizosphere soil P fertiliser rate (μg P g^{-1} soil)	
	50	100	50	100
Soil	---------- % ----------		---------- % ----------	
Resin-P_i	0.3	0.8	0.3	1.0
NaOH-P_i	40.4	42.6	48.8	46.1
NaOH-P_o	7.0	19.2	11.4	18.9
H_2SO_4-P_i	9.1	8.6	8.6	8.9
Residual-P	-7.4	-4.5	-8.2	-3.7
Plant	35.3	29.0	35.3	29.0
Total	84.8	95.8	96.3	100.1

[1] $\frac{\text{(P concentration in fertilised soil – P concentration in control soil)}}{\text{Fertiliser P added to soil}} * 100$ (see Table 5.11 Chapter 5 for details)

6.5 Conclusions

A glasshouse trial was set up to test the hypothesis that ryegrass, when grown with radiata, increases the P concentration in radiata needles while broom, when grown with radiata, has no effect on the needle P concentration. The trial results showed that P concentration in new shoot needles of radiata pine, broom shoot, and ryegrass shoot increased with increased rates of triple superphosphate application to a P-deficient Allophanic Soil, but the effects of ryegrass and broom on P nutrition of radiata seedlings depended on the soil P status. In the absence of P fertiliser addition (control treatment), P concentration in new shoot needles of radiata grown in association with broom was higher than that of radiata grown with grass. This is probably due to higher phosphatase activity in radiata rhizosphere soil in the presence of broom and/or N supply from N fixed by broom. However, when P fertiliser was added (50 and 100 μg P

g^{-1} soil) the new shoot needle P concentration was significantly lower when radiata was grown with broom than that when radiata was grown with grass. This is probably related to the growth of broom, which increased exponentially compared to a much lower rate of grass growth increase with increased rates of P applied. Therefore, broom may have removed much of the plant-available P in the soil as indicated by the consistently lower Bray-2 P concentration in the rhizosphere soil of radiata in association with broom than that in the rhizosphere soil of radiata in association with grass at the two high P rates.

Broom had five times higher dry matter yield than ryegrass when they were separately grown with radiata. Also, broom dry matter yield, when broom was grown with radiata, was twice that when broom was grown alone in half the soil volume. These results suggest that in moderate to high P fertile soils young radiata seedlings grow better under ryegrass than broom because broom grows vigorously in high P fertile soil and competes with radiata for P and other nutrients. It has been shown by others (Watt *et al.*, 2003c) that in spite of broom fixing atmosphere N, it can compete with radiata for N.

The P concentration in new shoot needles had a significant relationship with Bray-2 P and NaOH-P_i concentrations but not with resin-P_i concentration, suggesting that radiata seedlings were utilising P mainly from the NaOH-P_i pool. The extremely low resin-P_i pool in the soil was unable to supply all the P needs of the seedlings. The dry matter yield of radiata also had a strong relationship with P concentrations in Bray-2 P and NaOH-P_i extracts.

Broom yield, P uptake and grass shoot P concentration also had stronger relationships with NaOH-P_i when broom or grass was grown with radiata compared to when broom or grass was grown alone. This suggests that there was an influence of radiata rhizosphere on P nutrition in broom and ryegrass probably resulting from acidification and an increase in oxalate concentration and phosphatase activity in the rhizosphere soils, which may have increased plant availability of P to broom and grass.

The NaOH-P_i fraction constituted the highest percentage of P recovered from the fertiliser P added to this high P fixing soil. The second highest P recovery was in the plant tissues.

Chapter 7

Summary, Conclusions and Recommendations for Future Study

7.1 Need for the study

Phosphorus is an important nutrient in New Zealand *P. radiata* plantations as most of the soils are P deficient or marginally deficient and this element has been routinely applied to the plantations since the 1960's where appropriate (Hunter *et al.*, 1991; Payn *et al.*, 1998). However, most of the information available on the P fertiliser requirements of *P. radiata* was obtained from trials which were carried out under silvicultural regimes which were quite different from today. Nowadays, *P. radiata* forests in the country are mostly second rotation plantations with wider initial tree spacing and lower initial stocking of trees (400-800 trees ha^{-1}) compared to those prior to the 1990's (1200-2000 trees ha^{-1}) (MacLaren, 1993). The wider initial tree spacing creates potential for increased growth of understorey vegetation in forest stands, as light conditions below the canopy and nutrient resources are relatively better.

A review of literature showed that the above-ground understorey biomass is a significant proportion of the total above-ground biomass in *P. radiata* plantations during the first 5-10 years of tree growth. The presence of understorey vegetation in radiata forests during this period may lead to competition for nutrients (including P), light, and/or water depending on site fertility, climate, and the types of understorey species and their populations. It is also possible that the presence of certain understorey species under *P. radiata* may have synergistic effects on tree growth and nutrition.

Under the current silvicultural regimes with the potential for increased weed growth, the responses of *P. radiata* trees to P, and changes in P availability following P fertiliser application are expected to be more influenced by the interaction between the applied P fertiliser, the tree and the understorey vegetation than was the case in the past. Information on these interactions is required to determine appropriate P fertiliser management practices in *P. radiata* forest plantations, and to develop further a P fertiliser Decision Support System (PDSS) currently being constructed by New Zealand Forest Research Ltd.

7.2 Objectives of the study

The main objectives of this study are to investigate the influence of different rates of a soluble and a sparingly soluble P fertiliser (Triple superphosphate (TSP) and Ben-Geurier phosphate rock (BGPR)) and weed control, and their interactions, on the changes in soil P chemistry and the growth of 4-5-year-old second-rotation *P. radiata* trees. This study consisted of two field trials, one on an Allophanic Soil (Kaweka forest) and the other on a Pumice Soil (Kinleith forest). The two field trials were located in the central North Island of New Zealand. The effect of treatments on soil P fractions, P extracted by different soil tests, needle P concentration and tree growth were investigated one and two years after trial establishment. A glasshouse study was also conducted on *P. radiata* seedlings to complement the field trials. The glasshouse trial tested the hypothesis, based on the results of an earlier field trial (Richardson *et al.*, 1996), that when ryegrass is grown with *P. radiata*, it increases the P concentration in radiata needles (synergistic effect), while when broom is grown with *P. radiata*, it has no effect on the needle P concentration.

7.3 Field trials

The field trial results showed that the application of P fertilisers had no effect on tree growth at the two forests during the two year period of the trial, though it increased *P.*

radiata needle P concentrations in both forests. The reason for the absence of growth response to the application of P is that the trees were not P deficient as indicated by the needle P concentrations in the unfertilised trees, which were higher than the critical P concentration considered necessary to produce maximum radiata yield. However, the tree diameter at breast height (DBH) and the basal area (BA) significantly increased two years after understorey vegetation removal treatment at both Kaweka and Kinleith forests. At Kinleith forest the tree height also significantly increased two years after the understorey vegetation removal. The needle N and P concentrations for all treatments were higher than the critical N and P concentrations considered necessary to produce maximum radiata yield, respectively. This suggests that the growth increase due to weed removal treatment at both forests was probably due to an increase in the availability of soil water and nutrients other than P and N.

The P in the surface soils (0-10 cm soil depth) below the litter layer at the two forests was found to occur mainly in the labile organic P fraction (0.1 M NaOH extractable P_o). In the Allophanic Soil at the Kaweka forest the concentration of NaOH-P_o was 196 μg P g^{-1} soil, which was 41% of the total P, and in the Pumice Soil at the Kinleith forest it was 253 μg P g^{-1} soil which was 64% of total P.

The NaOH-P_i and the H_2SO_4-P_i concentrations in the soils had increased at both forests two years after TSP application at the rates of 100 and 200 kg P ha^{-1}. The concentration of resin-P_i increased only at the more P deficient Kaweka forest (Bray-2 P 4 μg P g^{-1}) and not at the moderate P fertility Kinleith forest (Bray-2 P 13 μg P g^{-1}). Meanwhile, BGPR (90% < 1.00 mm) application at the rates of 50, 100 and 200 kg P ha^{-1} increased H_2SO_4-P_i concentrations at both forests. The increase in the concentrations of the P fractions with increased rates of P application at both forests was highest for NaOH-P_i when TSP was applied, and highest for H_2SO_4-P_i when BGPR was applied. The largest pool of P, NaOH-P_o, was unaffected by the P fertiliser application.

Soil test P values (Bray-2 P, resin-P_i and Olsen P) increased with increased rates of application of TSP at both forests. Increased rates of BGPR application increased only resin-P_i and Bray-2 P concentrations. The agronomic effectiveness of BGPR depends on its rate of dissolution in the soil. But it was not possible to determine the amount of

BGPR dissolution in these soils because of the high degree of field variability. However, the H_2SO_4-P_i concentrations in the soils treated with BGPR indicated that higher amounts of BGPR dissolved in the more acidic Kinleith soil, which also received more rainfall during the trial period, than the Kaweka soil.

The removal of understorey vegetation at the Kinleith forest reduced the Bray-2 P, resin-P_i, and Olsen P concentrations in the soil, but at the Kaweka forest it increased the resin-P_i and Olsen P concentrations. These contrasting results are probably due to the difference in the weed species and the soil P status in the two forests. The deeper rooted understorey species at the Kinleith forest (Himalayan honeysuckle, buddleia and some toetoe) may have enhanced the plant-available P concentrations in the soil surface through litterfall (the pumping mechanism). In the Kaweka forest soils with low P status even with P application, the understorey vegetation (bracken fern and some manuka) reduced resin-P_i and Olsen P concentrations. This suggests that when the plant-available P concentration is low, some types of understorey vegetation tend to compete with *P. radiata* for P (an antagonistic effect). The understorey vegetation removal, however, had no effect on *P. radiata* needle P concentration.

The field trials provided some evidence of downward movement of P to a soil depth of 20 cm at the Kinleith forest two years after 200 kg P ha^{-1} was applied as TSP. But in the high P fixing, less porous Allophanic Soil at the Kaweka forest, there was no evidence of downward movement of P below 10 cm.

At both forest sites, the needle P concentrations were significantly correlated with soil P extracted by Bray-2, Olsen, resin, and NaOH-P_i tests. The Bray-2 P extractant gave the highest R^2 value. There was also a strong relationship between the needle P concentration and the concentration of NaOH-P_i and a weak relationship between the needle P concentration and the concentration of H_2SO_4-P_i. These results suggests that *P. radiata* is probably taking up P more from the pool of P adsorbed to allophane and Fe+Al oxides (NaOH-P_i) than from the Ca-P pool in high P fixing acidic soils.

7.4 Glasshouse trial

The objectives of the glasshouse trial were to compare the effects of ryegrass and broom on soil properties including the soil P dynamics in the rhizosphere, and the P nutrition and the growth of *P. radiata* when these plants were grown separately with *P. radiata* seedlings. This study was conducted on the Allophanic Soil from the Kaweka forest where one of the field trials was sited. The comparative effects of ryegrass and broom were tested at different rates of TSP fertiliser application to the soil.

A review of past literature (see Chapter 2) showed that many of the experiments conducted to study plant interferences have not been very successful. This was partly due to inappropriate experimental designs employed in those studies. For example, some of the experiments failed to keep the soil weight (or volume) explored by the roots constant across all treatments. Also, in some studies investigating the below-ground interference between plants, the above-ground interference was neither removed nor kept constant. In the experiment reported in this thesis, the below-ground interference between plants was investigated while the above-ground interference between plants was kept constant for all treatments. The below-ground interference was studied in pots which were partitioned using nylon mesh (43 μm opening) to stop plant roots from one compartment getting into the other, but allowing root interference between plants (radiata with ryegrass and radiata with broom) within the same compartment.

The results showed that the total dry matter yield of *P. radiata* was higher when *P. radiata* was in association with grass compared to when it was in association with broom at the application rate of 100 μg P g^{-1} soil. This is probably due to the competition for P and other nutrients between *P. radiata* and broom, as a result of the markedly higher broom dry matter yield at this P rate compared to the grass dry matter yield when they were grown with *P. radiata*. Broom had three to five times higher dry matter yield than ryegrass when they were separately grown with *P. radiata* at the high rates of P addition (50 and 100 μg P g^{-1} soil). The much higher root density of broom in the soil compared to that of grass when these plants were in association with radiata, at the P rate of 100 μg P g^{-1} soil, support this competition explanation. These results suggest that in moderate to high P fertility soils young *P. radiata* seedlings grow better

in association with ryegrass than broom because broom grows vigorously in high P fertile soil and competes with *P. radiata* for P and perhaps for other nutrients and water as well. It has been shown by others (Watt *et al.*, 2003c) that in spite of broom fixing atmospheric N, it can also compete with radiata for N.

Further evidence that there was competition for P is provided by the data of needle P concentration. It was observed that when P fertiliser was added (50 and 100 μg P g^{-1} soil) the radiata new shoot needle P concentration was significantly lower when radiata was grown with broom than when radiata was grown with ryegrass. However, in the absence of TSP application (control treatment), the P concentration in new shoot needles of radiata grown in association with broom were higher than that of radiata grown with grass. The effect of broom increasing the P nutrition of *P. radiata* could be due to broom increasing the N supply to radiata through N fixation and inducing higher phosphatase activity in the rhizosphere at low soil P concentrations. These results suggest that the understorey vegetation effects on *P. radiata* P nutrition depend on the P status of the soil.

The results also provided evidence of a beneficial effect of *P. radiata* on soil P availability to broom and ryegrass. The soils in the rhizosphere of grass and broom grown in association with *P. radiata* were acidified by the radiata roots. This acidification caused increased P availability in the rhizosphere soils as measured by Bray-2 P and resin-P_i tests when grass or broom were grown with radiata compared to when they were grown alone.

Acid phosphatase activity in soils under radiata, grass and broom decreased with an increased rate of P application, in agreement with other studies in the literature that have reported that at high P fertility levels the activity of these adaptive extracellular enzymes decreases. At all P rates, acid phosphatase activity was higher in the rhizosphere than in the bulk soils of radiata grown with broom. The phosphatase activity in the rhizosphere soil of radiata grown with broom was also higher than that of radiata grown with ryegrass. These results suggest that compared with ryegrass, broom root processes can increase the phosphatase activity in the rhizosphere soil of *P. radiata*. This effect of broom is probably due to N_2 fixation by this plant, which may have

increased N availability to radiata, and, thereby, stimulated the production of phosphatases (Olander and Vitousek, 2000).

The soil used in the trial had NaOH-P_o (127 μg P g^{-1} soil and 50.2% of total P) as the largest P fraction. Application of TSP increased NaOH-P_i, NaOH-P_o, and H_2SO_4-P_i concentrations in the soil, but decreased the residual-P concentration. Of these P fractions, NaOH-P_i increased at a much higher rate than the others, probably due to increased P fixation in this Allophanic Soil. The resin-P_i concentration, which is extremely low in this soil (1 to 3 μg P g^{-1} soil), remained the same. The majority of the added fertiliser P was recovered in the NaOH-P_i fraction (40-49%), while the second highest recovery was in plants (29-35%).

The NaOH-P_i concentration had a very high correlation with Bray-2 P concentrations, indicating that even though P fixation in the soil is high, some of the fixed P may be available to plants. The NaOH-P_i concentration in the radiata rhizosphere soil was lower than that in the radiata bulk soil and broom and grass rhizosphere soils under P deficient conditions (when no P fertiliser was applied). This is probably due to the radiata root processes, such as oxalate anion production, reducing fixation of P in soils.

The P concentration in radiata new shoot needles had significant relationships with Bray-2 P and NaOH-P_i concentrations but not with resin-P_i concentrations, suggesting that radiata seedlings were utilising P mainly from the NaOH-P_i pool. The extremely low resin-P_i pool in the soil was unable to supply all the P needs of the seedlings. The dry matter yield of radiata also had a strong relationship with P concentrations in Bray-2 P and NaOH-P_i extracts.

7.5 Overall conclusions

The results of the study reported in this thesis have shown that the application of P fertilisers had no effect on tree growth both at Kaweka and Kinleith forests during the two year period of the trial, though it increased radiata needle P concentration. One reason for the absence of growth response to the P application is that the trees were not

severely P-deficient. Another reason could be the short-term duration of the study. The tree growth response to P fertiliser application may be a slow process and, therefore, the trees did not show any growth response within two years after fertiliser application.

However, at both Kaweka and Kinleith forests, the understorey vegetation removal treatment increased stem diameter at breast height (DBH) and basal area (BA) two years after the treatment. These increases were most probably due to the understorey vegetation removal increasing the availability of soil water and nutrients other than N and P because *P. radiata* N and P concentrations for all treatments at both the forests were higher than the critical N and P concentrations, respectively.

In the highly P-deficient Kaweka forest soil the presence of understorey reduced resin-P_i and Olsen P concentrations, but in the moderate P fertility Kinleith forest soil the presence of understorey increased Bray-2 P, resin-P_i, and Olsen P concentrations in the soil. The deeper rooted understorey species at the Kinleith forest (Himalayan honeysuckle, buddleia and some toetoe) may have enhanced the plant-available P concentrations in the soil surface through litterfall (pumping mechanism) (synergistic effect). Whereas, at the Kaweka forest where the soil plant-available P is low, the understorey vegetation (bracken fern and some manuka) tend to compete with radiata for P (antagonistic effect). But the changes in soil P concentrations due to the understorey vegetation removal treatment were not reflected in the radiata needle P concentrations at both the forests.

In a glasshouse study, the application of P fertiliser to the P-deficient Allophanic Soil enhanced root-induced soil acidification in the *P. radiata* rhizosphere and this root-induced acidification increased P availability in the ryegrass and broom rhizosphere soils, as indicated by the Bray-2 P and resin soil P tests. The increased rate of P application, however, decreased acid phosphatase activity in soils under radiata, ryegrass and broom. When *P. radiata* was grown with broom, at all P rates the acid phosphatase activity in the rhizosphere of *P. radiata* was higher than in the bulk soil and the rhizosphere soil of *P. radiata* grown with ryegrass.

The results of the glasshouse study showed that the effects of ryegrass and broom on the P nutrition of radiata seedlings depended on the soil P status. In the absence of P fertiliser addition when broom was grown with *P. radiata*, the P concentration in new shoot needles of radiata was higher than that of radiata when it was grown with grass. However, when P fertiliser was added (50 and 100 μg P g^{-1} soil) broom had an antagonistic effect on *P. radiata*. The *P. radiata* new shoot needle P concentration was lower when *P. radiata* was grown with broom than that when *P. radiata* was grown with grass. In addition, in the high P fertile soil (application rate of 100 μg P g^{-1} soil), the dry matter yield of radiata was lower when it was grown with broom than when it was grown with ryegrass. This result suggest that in moderate to high P fertile soils, *P. radiata* seedlings grow better with ryegrass than with broom, because broom grows vigorously in high P fertile soil and competes with *P. radiata* for P and perhaps for other nutrients and water as well.

7.6 Future research

The results of this study have provided information for the first time on the effect of different rates of a soluble and a sparingly soluble P fertiliser and weed control and their interactions on the growth and P nutrition of *P. radiata* and soil P dynamics in an Allophanic Soil and a Pumice Soil under field conditions. The glasshouse trial conducted to study the interference of ryegrass and broom with *P. radiata* seedlings for P uptake also provided a better understanding of the interaction of P fertiliser, particular understorey vegetation and *P. radiata.* These studies have also generated some questions regarding the interaction of P fertilisers, understorey vegetation and *P. radiata.* The following studies are recommended for the future to address some of these questions:

(i) In this thesis, due to time limitation, the results of only the 1st two years of trial data were analysed. The response of trees to the treatments, however, may take a longer time and, therefore, the field trials need to be continued and the results analysed. The long-term duration of the trial would also help to study the effect of the understorey biomass cycling and the fertiliser P loss by leaching over a long-

period. Bulk density measurements are required to determine the total amount of fertiliser P losses as well as obtaining more accurate relationship between soil tests and plant nutrient concentrations.

(ii) Phosphatase activities in the rhizosphere soil of *P. radiata* in association with broom, and the associated needle P concentrations of *P. radiata* were higher than those when *P. radiata* was grown with ryegrass when no P fertiliser was added. These results were explained as being due to N fixation by broom. If this is true, can other understorey legumes also produce such results? Scott (2002) showed that in one of the soils he studied lucerne had a positive effect on tree growth and P uptake. He also reported that in some soils lucerne appeared to facilitate redistribution of P from the less labile to the more labile fraction. Studies on other understorey legumes need to be conducted under field conditions, as well as under glasshouse conditions, using improved experimental designs.

(iii) Understorey vegetation P concentration and biomass need to be collected to obtain a P balance sheet in the two forests. This may also provide further information on the type of interference between weeds and *P. radiata.*

(iv) *P. radiata* needles should also be analysed for nutrients other than N and P to determine whether the tree growth reduction under weeds is due to nutrients other than N and P.

(v) Water balance data also needs to be obtained to determine whether there is competition for soil moisture between understorey and *P. radiata* in the forests.

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Appendix 1 Past and current P fertiliser trials on *P. radiata* in New Zealand

No.	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
1.	Riverhead State Forest , north-west of Auckland	Waikare clay loam, Podzol Soil	Single Super-phosphate (SSP) and phosphate rock (PR) (376 and 672 kg P ha^{-1} broadcast and 57 g P per tree)	15 years (1951-1966)	1 year/first rotation	Diameter at breast height (DBH) were 168, 168 and 113 mm for SSP and 173, 191 and 147 mm for PR, respectively (control had 88 mm, P treatments were significantly different compared with control). Needle P concentrations were 0.08, 0.07, 0.07% for SSP and 0.07, 0.09, 0.08% for PR, respectively (control had 0.1%, not different from P treatments)	Mead and Weston (1972)
2.	Riverhead State Forest, north-west of Auckland	Waikare clay loam, Podzol Soil	0, 28, 56 and 112 g SSP, and 56 g SSP + 28 g ammonium sulphate per tree	4 years (1966-1970)	1 year/first rotation	Tree height increased compared with control (165, 195, 227, 252, 210 cm, respectively). Needle P was not different between treatments (0.07, 0.07, 0.07, 0.08 and 0.07%, respectively). For routine management 112 g per seedling of SSP (11 g P) was recommended	Ballard (1978)
3.	Riverhead State Forest, north-west of Auckland	Waikare clay loam, Podzol Soil	P (0, 15, 30, 45 g P per seedling) and N fertilisers (0, 15, 30 g N per seedling) + site preparation treatments	2 years (1973-1975)	1 year/first rotation	Rate of *c.* 17 g P per seedling was found to be optimal for most P-responsive sites	Ballard and Mead (1976)

	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
4.	Kaingaroa State Forest, Rotorua	Pumice Soil	(Control; 5.2 g N + 10 g P + 4.5 g Mg, P as SSP; 4.5 g N + 9.5 g B + 7.9 g Mg; and 9 g N + 19 g P + 15.8 g Mg per seedling, P as MagAmp 8-17-0-14) + ripping treatment.	3 years (1965-1968)	1 year/first Rotation	Tree heights were 88, 135, 168, and 180 cm, respectively for ripped sites. For unripped sites, they were 34,102, 124, and 145 cm, respectively.	Mead (1968)
5.	Waiwhero, Nelson	Rosedale hill soil, Pallic Soil	Control, 0.4 g B, and 0.3 g B + 8.5 g P per seedling. P as SSP.	4 years (1967-1971)	1 year/first rotation	Tree heights were 125, 105 and 268 cm, respectively	Ballard (1978)
6.	Waiwhero, Nelson	Mapua hill soil, Pallic Soil	Gorse control (g.c), no g.c, g.c or no g.c + (8.5 g P + 1.1 g B per seedling at establishment in 1966 and 112 kg P + 8.8 kg B ha^{-1} in 1970). P as boronated SSP	7 years (1966-1973)	1 year/first rotation	In 1969, needle P concentration was 0.08% for gorse control, 0.07% for no g.c, 0.08% for g.c + (P + B), and 0.09% for no g.c + (P + B). In 1973, tree heights were 401, 368, 801, 688 cm, respectively.	Jack *et al.* (1972)

	Trial site	Soil type	Treatments	Duration	Tree age/ rotation	Results	Reference
7.	Motueka State Forest, Nelson	Rosedale hill soil, Pallic Soil	Control, B, N + B, P + B, N + P + B. P = 100 kg P ha^{-1} in 1968; B = 2 kg B ha^{-1} in 1968 and 4 kg B in 1971; N = 4 g N per seedling in 1968 and 13 g N per seedling in 1969. P as SSP	7 years (1968-1975)	1 year/first rotation	Significantly higher tree height (at age 5 yrs) and basal area (at age 7 yrs) with P than without P	Mead *et al.* (1976)
8.	Craigieburn, Wesland	A pakihi terrace soil, Podzol Soil	(Control, PR (60 kg P ha^{-1}), SSP + blood and bone (21 kg P + 8 kg N) ha^{-1}, SSP + blood and bone + potash (28 kg P + 10 kg N + 28 kg K) ha^{-1}) + site preparations	6 years (1965-1971)	1 year/first rotation	Tree heights were 2.2, 2.9, 3.9, and 3.8 m, respectively, for mound sites. For flat sites, they were 1.4, 2.2, 3.2, and 2.4 m , respectively, indicating the need for drainage and N + P fertilisers to obtain reasonable growth	Washbourn (1972)
9.	Riverhead State Forest, north-west of Auckland	Waikare clay and Mata clay hill soils, Podzol Soils	0 and 225 kg P ha^{-1} (P applied as mixture of P fertilisers: 75% SSP, 15% ground Nauru PR, 10% ground serpentine rock)	24 years (1952-1976)	20- to 24-years/first rotation	In P treated plots, tree height (33.1 m) and volume (981 m^3 ha^{-1}) were much higher compared with control (19.5 m; 206 m^3 ha^{-1}, respectively)	Mead and Gadgil (1978)

	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
10.	Riverhead State Forest, north-west of Auckland	Waikare clay loam, Podzol Soil	0, 22.5, 45, 220 kg P ha^{-1} applied as SSP	21 years (1955-1976	27 years/ first rotation	A marked response of basal area and volume to P fertiliser. The optimum rate probably between 45-220 kg P ha^{-1}	Mead and Gadgil (1978)
11.	Wangapoua Forest, Auckland	A firm coarse blocky structured clay, Podzol Soil	0, 625 kg SSP ha^{-1} (at trial establishment), 1250 kg SSP (at trial establishment), 2500 kg SSP (at trial establishment), 625*2 kg SSP (at trial establishment and after 10 yrs), 625*4 kg SSP (at trial establishment and after 5, 10, 15 years), 625 kg SSP applied 5 years after trial establishment, 625 kg SSP applied at trial establishment and reapplied if ..	5 years (1967-1972)	6 years/first rotation	Needle P concentration was 0.13% in P treated plots (2 years after P applied) and 0.08% in control (5 years after trial established). Tree height significantly increased in P treated plots compared with control plots (12 years after P applied). Basal area was significantly increased by P application after thinning (5 years after P applied).	Hunter and Graham (1982)

	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
			foliar P < 0.13%, and 1250 kg SSP ha^{-1} at trial establishment and re-applied if foliar P < 0.13%				
12.	Glenbervie Forest, Auckland	A firm clay with a strong to medium blocky structure, Podzol Soil	Similar to the above treatments	5 years (1970-1975)	5 years/first rotation	Needle P concentration was 0.21% in P treated plots (2 years after P applied) and 0.12% in control (5 years after trial established).	Hunter and Graham (1982)
13.	Maramarua Forest, Auckland	A very firm, very coarse structured silty clay, Podzol Soil	Similar to the above treatments	5 years (1971-1976)	8 years/second rotation	Needle P concentration was 0.18% in P treated plots (2 years after P applied) and 0.08% in control (5 years after trial established).	Hunter and Graham (1982)
14.	Riverhead State Forest, north-west of Auckland	Waikare clay loam, Podzol Soil	Similar to the above treatments	5 years (1973-1978)	6 years/first rotation	Needle P concentration was 0.13% in P treated plots (2 years after P applied) and 0.06% in control (5 years after trial established).Tree height significantly increased by P treatments (5 years after P applied). Basal area significantly increased by P treatments (6 years after P applied).	Hunter and Graham (1982)

	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
15.	Maramarua Forest, south of Auckland	Clay soil, Podzol Soil	Control, 52 kg P ha^{-1} applied as SSP, 52 and 104 kg P ha^{-1} applied as Christmas Island "C" phosphate	9 year (1955-1964)	7 years/second rotation	Tree heights in P treated plots (18 m for SSP, 15.4 m and 20.1 m for 52 and 104 kg P applied as PR) were higher than control (13.4 m). Volume in P treated plots (146.8 $m^3 ha^{-1}$ for SSP, 84 and 181.5 $m^3 ha^{-1}$ for 52 and 104 kg P ha^{-1} applied as PR) were higher than control (34.9 $m^3 ha^{-1}$). Needle P concentrations in P treated plots were greater than control, but in all treatments needle P were < 0.13%) (8 years after P applied)	Mead (1974)
16.	Waipoua State Forest, northwest of Auckland	Podzolised Sand (P ret 0%), Podzol Soil	SSP, "A grade" PR, Citraphos from Christmas Island (75 and 150 kg P ha^{-1}), and control	4 years (1978-1982)	7 years/first rotation	P application increased needle P concentrations compared with control (0.17% for SSP, 0.16% for A grade PR, 0.15% for Citraphos, and 0.12% for control). After 3 years P application, BA in P treated plots was higher than control, but there was no difference between P fertiliser forms.	Hunter and Graham (1983)
17.	Riverhead State Forest, northwest of Auckland	A weakly podzolised clay (P ret 48%), Podzol Soil	SSP, "A grade" PR, Citraphos from Christmas Island, "C grade" PR (75 and 150 kg P ha^{-1}), and control	4 years (1978-1982)	4 years/first rotation	P application increased needle P concentrations compared with control (0.10% for SSP, 0.10% for A grade PR, 0.10% for Citraphos, 0.08% for C grade PR, and 0.08% for control). After 3 years P application, BA in P treated plots was higher than control. The effectiveness of P fertiliser followed the 2% citric acid solubilities. "C grade" PR was not effective.	Hunter and Graham (1983)

	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
18.	Tairua State Forest, Coromandel Peninsula, Auckland	An old deeply weathered ash (P ret 93%), Allophanic Soil	Similar to the above treatments	4 years (1978-1982)	4 years/first rotation	The effect of P application was not significant on needle P concentrations (0.12% for SSP, 0.12% for A grade PR, 0.12% for Citraphos, 0.10% for C grade PR, and 0.10% control), nor on BA.	Hunter and Graham (1983)
19.	Waipoua State Forest, northwest of Auckland	Podzolised Sand (P ret 0%), Podzol Soil	SSP, "A grade" PR from Christmas Island (75 and 150 kg P ha^{-1}), and control	7 years (1978-1985)	7 years/first rotation	Needle P concentrations in P treated plots (0.17% for SSP; 0.16% for PR) were significantly higher than that in control (0.10%). No significant effect of all types of P fertiliser on basal area (BA). Bray-1 P concentrations at 0-10 cm soil depth were 15, 14, 5 μg P g^{-1} soil, respectively. Total P in the soil were 709, 495, 466 μg P g^{-1} soil, respectively.	Hunter and Hunter (1991)
20.	Riverhead State Forest, northwest of Auckland	A weakly podzolised clay (P ret 48%), Podzol Soil	Similar to the above treatments	7 years (1978-1985)	4 years/ first rotation	Needle P concentrations in P treated plots (0.13% for SSP, 0.11% for PR) were higher than that in control (0.08%). BA in P treated plot was greater than that in control (8.9 m^2 ha^{-1} and 7.5 m^2 ha^{-1} of increment, respectively). Bray-1 P concentrations at 0-10 cm soil depth were 52, 62, 4 μg P g^{-1} soil, respectively. Total P in the soil were 1294, 1639, 1300 μg P g^{-1} soil, respectively.	Hunter and Hunter (1991)

	Trial site	Soil type	Treatments	Trial duration	Tree age/ rotation	Results	Reference
21.	Tairua State Forest, Coromandel Peninsula, Auckland	An old deeply weathered ash (P ret 93%), Allophanic Soil	Similar to the above treatments	7 years (1978-1985)	4 years/ first rotation	Needle P concentration in P treated plots (0.12% for SSP, 0.11% for PR) were higher than that in control (0.09%). BA in P treated plot was greater than that in control (4.9 m^2 ha^{-1} and 1.6 m^2 ha^{-1} of increment, respectively). Bray-1 P concen-trations at 0-10 cm soil depth were 7, 15, 2 μg P g^{-1} soil, respectively. Total P in the soil were 827, 968, 930 μg P g^{-1} soil, respectively.	Hunter and Hunter (1991)
22.	Riverhead State Forest, north-west of Auckland	A Waikare clay, Podzol Soil	0, 25, 50, and 75 kg P ha^{-1} as either acidulated PR (0, 20, 25, 30% aci-dulated), or TSP	6 years (1987-1993)	4 years/se-cond rotati-on	The effect of P treatments on BA was highly significant, but not significantly different between P rates and forms. Needle P concentrations were 0.084, 0.095, 0.100, 0.110%, respectively.	Skinner *et al.* (1995)