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MAGNESIUM AND POTASSIUM FERTILISER EFFECTS ON FOLIAR MAGNESIUM AND POTASSIUM CONCENTRATIONS AND UPPER MID-CROWN YELLOWING IN PINUS RADIATA

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ABSTRACT

Upper mid-crown yellowing (UMCY) is a disorder in *Pinus radiata* D.Don caused mainly by a high potassium/magnesium (K/Mg) ratio in the soil exchange complex and in the tree needles. To study the effects of a range of soil exchangeable K/Mg ratios on potassium and magnesium uptake and UMCY in *P. radiata,* a trial was established in September 1996 on a Pumice Soil in northern Kaingaroa Forest in the central North Island of New Zealand in a second-rotation stand of 20-year-old *P. radiata*. The trial tested the effects of magnesium applied as kieserite at 200 kg Mg/ha and potassium applied as potassium sulphate at 200 and 400 kg K/ha on soil-exchangeable and soil-solution magnesium and potassium, on tree needle magnesium and potassium, and on severity of UMCY.

The applications of magnesium and the two rates of potassium significantly ($p<0.05$) increased soil-exchangeable and soil-solution magnesium and potassium concentrations respectively in the top 10 cm soil depth during the first 2 years of the trial (1997 and 1998). Magnesium application significantly ($p<0.05$) reduced the soil-exchangeable K/Mg ratio from 0.7–1.3 (control treatment) to 0.2–0.3, whereas the low and high rates of potassium application significantly increased this ratio to 0.8–1.7 and 1.3–2.5 respectively in the 2 years.

The magnesium fertiliser application significantly ($p<0.1$) increased tree foliage magnesium concentration in 1999, but had no effect on foliage K/Mg ratios in any of the 4 years of sampling (1997, 1998, 1999, and 2002). Potassium fertiliser at the high rate significantly ($p<0.1$) increased the foliar potassium concentration in 1998 and 2002. Neither magnesium nor potassium fertiliser application had any effect on the change in foliar magnesium, potassium, or K/Mg ratio between 1997 and any of the other years sampled.

Individual tree UMCY values ranged from 1 to 6 in a system of increasing severity from 1 to 8. Magnesium fertiliser significantly (p=0.074) reduced UMCY values (assessed in 1997 and 2001) in the 2001 scoring. Similarly, the UMCY value significantly (p=0.055) decreased from 1997 to 2001 for the magnesium fertiliser treatment compared to the control treatment and high potassium rate treatment. Potassium fertiliser application had a significant effect neither on UMCY values nor on changes in UMCY values between 1997 and 2001. The severity of UMCY was not related to the soil-exchangeable K/Mg ratio in spite of the widely different soil-exchangeable K/Mg ratios (0.3 to 2.0 in the 0–10 cm soil depth) produced by the fertilisers. Nor was it related to the foliar K/Mg ratio. The reasons for this could be that the site was not high risk for UMCY during the trial period, the trees were possibly taking significant amounts of potassium and/or magnesium from deeper layers of soil which were probably not strongly influenced by the fertiliser, the amounts of potassium applied were not excessive, and/or the impact of the fertilisers was relatively short-term.

Keywords: foliar magnesium; foliar potassium; foliar potassium/magnesium ratio; soil magnesium; soil potassium; soil potassium/magnesium ratio; kieserite; potassium sulphate

INTRODUCTION

Magnesium deficiency symptoms in *Pinus radiata* have been observed throughout New Zealand, but are most prevalent on Pumice Soils in the central North Island, the Podzols of Westland, and the Brown Soils of Otago, Southland, and Nelson (Hunter *et al.* 1991; Maclaren 1993; Hunter 1996). Magnesium deficiency is considered to be the main cause of UMCY, a disorder of needle yellowing and subsequent premature loss from the upper mid-portion of tree crowns, particularly in mid-rotation stands of *P. radiata* (Beets *et al.* 1993). Severe UMCY can lead to substantial needle loss from the upper crown, a reduction in tree diameter growth (Beets & Jokela 1994), and lower wood density (P.Beets, unpubl. data).

High ratios of soil-exchangeable K/Mg and foliar K/Mg concentrations have been shown to increase the incidence and severity of UMCY (Beets & Jokela 1994; Olykan *et al.* 2001). An increase in foliar K/Mg ratios has been observed after repeated harvesting of *P. radiata* on Pumice Soils of the central North Island (Will 1966; Ballard 1978). These changes in foliar K/Mg ratios reflect changes in pools of soil-exchangeable potassium and magnesium caused by the removal of organic topsoil during harvesting operations (Ballard 1978; Beets & Jokela 1994). Recently, Beets *et al.* (2003) reported that at Puruki Forest magnesium deficiency symptoms in *P. radiata* were positively correlated with exchangeable and soil-solution potassium concentrations at 50–100 cm soil depth and negatively correlated with exchangeable magnesium concentration at 0–10 cm soil depth. Exchangeable potassium concentration was positively correlated with the thickness of a lapilli layer at 50–100 cm depth and this was suggested as a reason for the widespread occurrence of magnesium deficiency symptoms on volcanic ash soils when the surface horizon is dry after years of sub-normal rainfall, even in stands with a history of magnesium fertiliser treatment.

Magnesium fertiliser application can reduce the soil and foliar K/Mg ratios and the severity of UMCY (Olykan *et al.* 2001). However, there is no information available on whether application of potassium fertiliser will change the K/Mg ratio in the soil exchange complex and foliage, and cause increased severity of UMCY. Studies on other crops have shown that potassium has an antagonistic effect on magnesium uptake (Mengal & Kirkby 1987; Barber 1984). It is not known whether this is true in *P. radiata* under forest conditions although Sun & Payn (1999) have shown in sand culture studies that, at low magnesium concentrations, increased potassium concentration in the culture solution enhanced the development of magnesium deficiency symptoms in *P. radiata* seedlings. Given the apparent importance of the potassium status of the soil and that field trials using magnesium fertilisers have been widely studied (Will 1961; Hunter *et al.* 1986; Payn *et al.* 1995; Hunter 1996; Mitchell *et al.* 1999; Olykan *et al.* 2001), there was a need for a clearly defined field experiment that manipulated the soil-exchangeable K/Mg ratios by the addition of potassium and magnesium fertilisers, and investigated their effects on tree nutrition and visual health. Therefore, we conducted a study under field conditions to test the hypothesis that excessive potassium fertiliser additions can increase the soil and foliage K/Mg ratios and cause increased UMCY severity.

MATERIALS AND METHODS

Trial Site and Design

The study was conducted in northern Kaingaroa Forest, in the central North Island of New Zealand, in a mid-rotation stand of *P. radiata*. The previous crop of *P. nigra* J.F.Arnold subsp. *laricio* (Poir.) Maire planted in 1918–19 was felled in 1975. Site preparation included a partial spray with desiccant (formula unknown) in January 1976, and burning in February. The site was windrowed and bedded in July, and the current crop was planted in July–August 1976 at 1667 stems/ha, with dead trees replaced by new seedlings in 1977. The planting material was grown from seed collected in 1972 from Cpt 950, Kaingaroa Forest. The seeds were from genetically diverse, largely unimproved parents. A releasing spray (formula unknown) was applied in October 1976, with a further spray in October 1977 (4.6 litres Atrazine plus 3.1 litres Amitrole T plus 130 ml surfactant in 340 litres/ha). The stand was thinned to waste to 578 stems/ha in August 1981, with a final production-thinning to 259 stems/ha in March 1993. The stand was pruned to 2.2 m (562 stems/ha) in December 1981, with a further pruning lift to 4.0 m (370 stems/ha) in February 1984 and a final pruning lift to 5.8 m (259 stems/ha) in May 1985. The stand was copper sprayed for dothistroma needle-cast in November 1989.

The primary understorey species in the forest were blackberry (*Rubus fruticosus* agg.), crown fern (*Blechnum discolor* (Forst.f.) Keys), pampas grass (*Cortaderia selloana* (Schult.) Asch. & Graebe), other grasses, and flat weeds. The stand was adjacent to a 16-year-old *P. radiata* stand in which 89% of the trees had UMCY symptoms with an average value of 3.15 (in a scoring system with severity increasing from 1 to 8 — *see* "UMCY Analysis"). The mean annual rainfall at the site was 1562 mm. The soils were derived from rhyolite flow-tephra from the latter stages of the Taupo eruption (1800 years BP), and they belong to the Pumice Soils (Kaingaroa loamy sand) in the New Zealand Soil Classification (Hewitt 1993) and Typic Udivitrand in the US Soil Taxonomy (Mitchell 2000). Soil pH (0–10 cm depth) (1:2.5 w/w soil to water ratio) was 5.6 and exchangeable magnesium, potassium, and calcium were 0.6, 0.5, and 3.4 $\mathrm{cmol}_{(+)}$/kg soil respectively. Effective cation exchange capacity (sum of exchangeable magnesium, potassium, calcium, and exchange acidity) was 6.0 $\mathrm{cmol}_{(+)}$/kg soil.

The trial consisted of four treatments: 200 kg Mg/ha applied as kieserite ($MgSO_4.H_2O$), 200 and 400 kg K/ha applied as potassium sulphate (K_2SO_4), and a no-fertiliser control. Each treatment was replicated five times to give 20 plots in total, arranged in a randomised complete block design. The treatments were broadcast-applied in September 1996. The plot size was 50 × 50 m with a 10-m buffer around each 30 × 30-m (0.09-ha) inner measurement plot consisting of approximately 20 trees.

Soil Sampling and Analysis

Soil samples were collected in March 1997 (approximately 180 days after fertiliser application) from the top 10 cm of each plot. Twenty 2-cm-diameter soil cores were collected at random and combined to make a bulk sample for each plot. Any fresh litter (L horizon) was not included in the sampling. However, the top 10-cm soil samples included the F and H horizons. A second set of soil samples was collected in March 1998 (approximately 550 days after fertiliser application) from the top 10 cm of each plot by randomly taking six 18 × 18 × 10-cm blocks of soil (Mitchell 2000). Smaller sub-samples from these blocks of soil were sampled for chemical analysis after thorough mixing. A different sampling procedure was used in 1998 because large blocks of soil were required for another study.

Soil solutions were extracted from one portion of the field-moist soils by centrifugation at 12 000 rpm (17 200 relative centrifugal force, RCF) in a refrigerated centrifuge at 4°C within 2 days of sample collection. The pH of the solution was measured immediately after centrifugation. Concentrations of magnesium, potassium, and calcium in the solution were measured by atomic absorption spectrometry.

The other portions of the field-moist soils were air-dried and ground to pass through a 2-mm sieve. Soil samples were analysed for exchangeable magnesium, potassium, and calcium after extraction with 1 *M* NH_4OAc buffered at pH 7.0 (Blakemore *et al.* 1987) followed by determination of the concentrations of magnesium, potassium, and calcium in the extracts by atomic absorption spectrometry.

Foliar Sampling and Analysis

Foliar samples were collected from the trial in March 1997, 1998, 1999, and 2002. Fully extended current needles were collected from secondary branches in the upper third of the crown of 12 randomly chosen trees per plot (Beets & Jokela 1994). Samples were oven-dried at 70°C and analysed for magnesium and potassium by atomic absorption spectrometry after they had been digested in H_2SO_4/H_2O_2 mix (Nicholson 1984).

Delta foliar magnesium, potassium, and K/Mg were calculated by subtracting plot treatment means for 1997 from those for 1998. Similarly, delta foliar magnesium, potassium, and K/Mg were calculated between 1997 and 1999, and 1997 and 2002.

UMCY Assessment

UMCY scoring was carried out from the ground in December 1997 and November 2001. The upper third of the crown of measurement trees was visually assessed and assigned an UMCY severity value ranging from 1 (for A+ trees) to 8 (for D- trees) as described by Beets & Jokela (1994):

1 = A+ Healthy upper crowns;

2 = A- Yellow needle tips sub-apically; full upper crowns with high retention of 2-year-old needles;

3 = B+ Yellow needle tips and thin crowns sub-apically, with poor retention of 2-year-old needles;

4 = B- Yellow 1- and 2-year-old needles and thin upper crowns with low needle production and retention on secondary branches;

5 = C+ Hollow zone caused by death of secondary branches occupying less than half the width of the upper crown;

6 = C- Hollow zone as for C+, but occupying more than half the width of the upper crown;

7 = D+ As for C-, but with one or more dead primary branches also present in the UMCY zone;

8 = D- Zone with dead primary branch whorls in upper crown — sometimes also associated with top death.

Delta UMCY was calculated by subtracting individual tree data for 1997 from individual tree data for 2001. Delta UMCY assessed using individual tree data is a better approach than delta UMCY assessed by subtracting mean UMCY of plots because the tree-to-tree variability is taken into consideration in the former approach.

Statistical Analysis

The soil-solution and soil-exchangeable cation results were analysed for significant differences between treatments using the Generalised Linear Modelling (GLM) procedure (SAS Institute 1996). Where the effect of the treatments had been significant, Duncan's Multiple Range Test was used to compare means at a confidence interval of 0.05. The changes in concentrations of soil-solution and soil-exchangeable cations and K/Mg equivalent ratios between the 2 years of sampling for individual treatments were subjected to a similar analysis. The Duncan's Multiple Range Test was used to compare means at a confidence interval of 0.05.

The foliage data and delta foliage concentrations were analysed for significant differences between treatments using the GLM procedure. The changes in foliar cation concentrations and K/Mg ratio between the 2 years of sampling for individual treatments were subjected to a similar analysis. Where the effect of the treatments had been significant, Duncan's Multiple Range Test was used to compare means at a confidence interval of 0.05. However, as there were a limited number of significant differences at $p= 0.05$, a confidence interval of 0.1 was also considered.

Individual tree data of UMCY and delta UMCY were analysed for significant differences between treatments using the GLM procedure. Where the effect of the treatments had been significant, Duncan's Multiple Range Test was used to compare means at a confidence interval of 0.05. As there were no significant differences at $p= 0.05$, a confidence interval of 0.1 was also considered.

Spearman correlation coefficients (r) were calculated to identify relationships between delta UMCY value and delta foliar potassium, magnesium, and K/Mg ratio.

RESULTS

Effect of Magnesium and Potassium Fertilisers on Concentrations of Soil-solution Cations

Soil-solution magnesium, potassium, and calcium

Magnesium fertiliser application significantly ($p<0.015$) increased soil-solution concentrations of magnesium in the 0–10 cm soil layer in 1997 and 1998 samplings (Fig. 1) compared to the control treatment and the two potassium fertiliser treatments. However, there was a significant ($p=0.022$) decrease in solution magnesium concentrations in the magnesium fertiliser treatment from 1997 to 1998. Potassium fertiliser application had no effect on soil-solution magnesium concentrations in either year.

Potassium fertiliser application at 400 kg K/ha significantly ($p<0.004$) increased soil-solution potassium concentrations in the 0–10 cm soil layer in both years of sampling compared to the control and magnesium fertiliser treatments, and the 200 kg K/ha treatment in the 1997 sampling (Fig. 1). As was found for soil-solution magnesium, there was a significant ($p<0.012$) decrease in solution potassium concentrations in both potassium fertiliser treatments from 1997 to 1998. Potassium application at 200 kg K/ha and magnesium application had no significant effect on soil-solution potassium concentrations in either year of sampling (Fig. 1).

There were no differences in soil-solution calcium concentrations between treatments in either year of sampling. There were, however, significant ($p<0.054$) decreases of 0.1–0.6 mmol/litre in soil-solution calcium in all fertiliser treatments from 1997 to 1998.

K/Mg equivalent ratio

The application of magnesium and potassium fertilisers produced a range of soil-solution K/Mg equivalent ratios (Fig. 1). In the 1997 samples, potassium fertiliser treatment significantly ($p=0.0004$) increased the mean K/Mg equivalent ratio from 2.6 in the control treatment to 9.3 for the 400 kg K/ha treatment and 6.0 for the 200 kg K/ha treatment. In the 1998 samples, the ratios for the 400 and 200 kg K/ha treatments decreased to 4.9 and 3.9 respectively, although none of the changes from 1997 to 1998 were significant. The differences between the ratios for both potassium fertiliser treatments and the control treatment in the 1998 sampling were significant ($p<0.0001$). The application of magnesium fertiliser had no effect on soil-solution K/Mg equivalent ratio compared to the control treatment in either year of sampling.

Effect of Magnesium and Potassium Fertilisers on Soil-exchangeable Cations

Exchangeable magnesium, potassium, and calcium

Magnesium fertiliser application significantly ($p<0.0001$) increased soil-exchangeable magnesium compared to the control treatment in the 0–10 cm soil layer in both years of

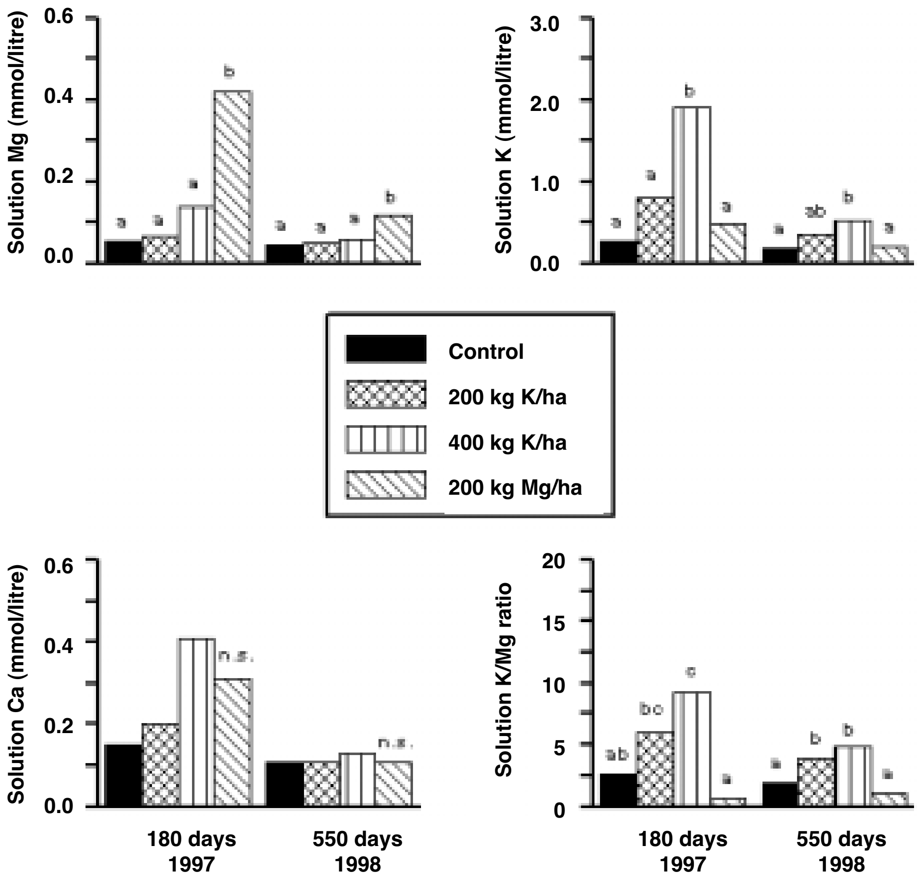

FIG. 1–Effect of magnesium and potassium fertilisers on soil-solution concentrations of magnesium, potassium, calcium, and K/Mg equivalent ratio in the top 10-cm soil layer at northern Kaingaroa Forest, 180 and 550 days after application. Means with the same letter are not significantly different at p=0.05; n.s. = no significant difference between treatment means at p=0.05.

sampling (Fig. 2). The increases in exchangeable magnesium equate to approximately 124 kg Mg/ha in 1997 and 88 kg Mg/ha in 1998 (bulk density used in the conversion was 0.70 g/cm^3). These represent increases over the control treatment value of approximately 240% and 170% in the 1997 and 1998 samplings, respectively. From these data it is estimated that 62% and 44% of magnesium applied remained in the 0–10 cm depth 6 and 18 months after fertiliser application. The remainder of the applied magnesium may have leached below 10 cm depth, been taken up by the trees, or been immobilised in the soil. The application of potassium fertiliser had no significant effect on exchangeable magnesium concentrations in either the 1997 or 1998 samplings. There were no significant differences in mean exchangeable magnesium concentrations from 1997 to 1998 for any treatment.

Potassium fertiliser application at 400 kg K/ha significantly ($p<0.0002$) increased soil-exchangeable potassium over the control treatment in both years of sampling (Fig. 2). The

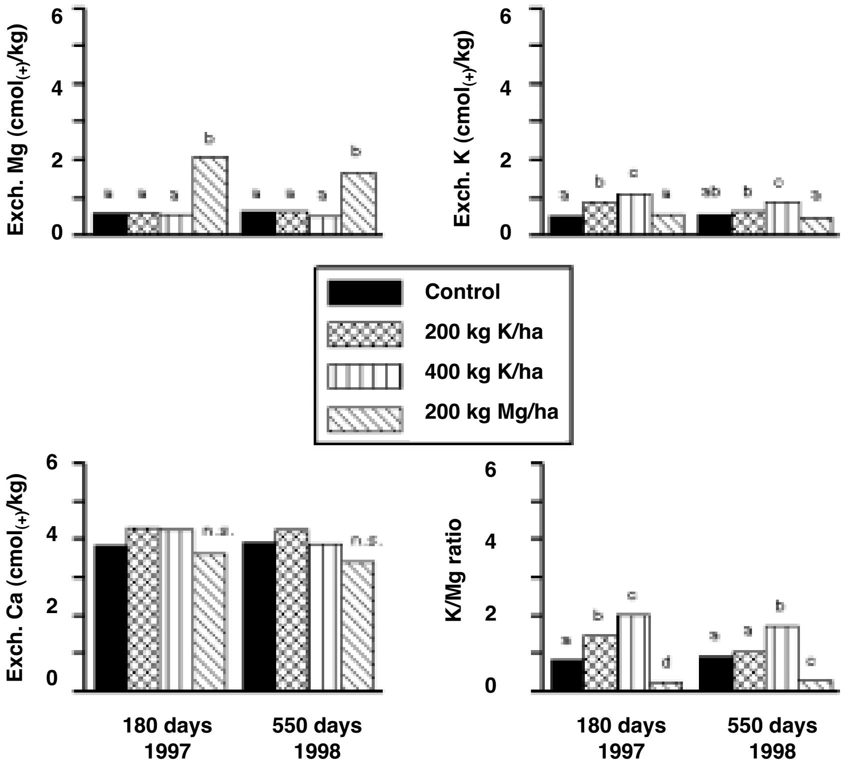

FIG. 2–Effect of magnesium and potassium fertilisers on soil-exchangeable magnesium, potassium, and calcium, and K/Mg ratio in the top 10-cm soil layer at northern Kaingaroa Forest, 180 and 550 days after application. Means with the same letter are not significantly different at $p=0.05$; n.s. = no significant difference between treatment means at $p=0.05$.

increases over the control treatment equate to approximately 115% in 1997, but only 60% in 1998. From the increase in exchangeable potassium concentrations it is estimated that 40% and 22% of potassium applied remained in the 0–10 cm soil depth in the 1997 and 1998 samplings, respectively. The reduction in soil-exchangeable potassium from 1997 to 1998 was significant at $p=0.035$. Potassium fertiliser applied at 200 kg K/ha significantly ($p<0.05$) increased soil-exchangeable potassium over the control treatment by approximately 70% in 1997, but only by 16% in 1998 which was not significant. The decrease in soil-exchangeable potassium from 1997 to 1998 for the 200 kg K/ha fertiliser treatment was significant at $p=0.037$. Magnesium fertiliser application had no significant effect on exchangeable potassium concentrations in either year.

Neither magnesium nor potassium fertiliser application had any effect on soil-exchangeable calcium in either year of sampling (Fig. 2) despite significant increases in soil-solution calcium as a result of potassium (400 kg K/ha treatment) fertiliser application in 1997 (Fig. 1). There were no significant differences in soil-exchangeable calcium concentrations from 1997 to 1998 for any of the fertiliser treatments.

Exchangeable K/Mg equivalent ratio

Magnesium fertiliser application significantly ($p<0.0001$) decreased the soil-exchangeable K/Mg ratio from 0.9 in the control treatment to 0.3 in 1997 (Fig. 2). This reflects increases in exchangeable magnesium due to magnesium fertiliser application. Potassium fertiliser application significantly ($p<0.0005$) increased the soil-exchangeable K/Mg equivalent ratio to 1.5 for the 200 kg K/ha treatment and 2.0 for the 400 kg K/ha treatment in 1997. However, in 1998, due to smaller effects on exchangeable potassium, the exchangeable K/Mg equivalent ratio for the 200 kg K/ha treatment was not significantly different from that of the control treatment (1.1 *versus* 0.9 respectively). There was a significant ($p=0.025$) decrease in the exchangeable K/Mg ratio for the 200 kg K/ha treatment from 1997 to 1998. In 1998, the decreases in the exchangeable K/Mg equivalent ratio in the magnesium fertiliser treatment were similar to those recorded in 1997, whereas potassium fertiliser application at 400 kg K/ha significantly ($p=0.002$) increased the ratio to 1.7. There were no significant differences in the K/Mg ratios between the 2 years of sampling for the magnesium and high potassium fertiliser treatments.

Effect of Magnesium and Potassium Fertilisers on Foliar Cations

Foliar magnesium

Foliar magnesium concentrations in the control treatment ranged from 0.08% to 0.12% over the 5.5 years of sampling (Fig. 3) and were marginal to satisfactory for tree growth based on the standard values (0.07–0.1%) of Will (1985). In the 5.5 years after application, magnesium fertiliser had no consistent significant effects on foliar magnesium concentrations. In the 1999 sampling, however, there was a significant ($p=0.047$) increase in foliar magnesium concentrations in the magnesium-treated trees compared to the control treatment. There were no consistent trends in the changes in foliar magnesium concentrations between the different years sampled. Magnesium fertiliser appears to have significantly ($p=0.077$) increased foliar magnesium concentrations from 1997 to 1998. However, this was the only change in foliar magnesium concentration between years that could be attributed to magnesium fertiliser application. There was a significant ($p<0.001$) decrease in foliar magnesium concentrations across all treatments from 1998 to 1999, suggesting that environmental factors had a greater influence on changes in foliar magnesium concentrations between the different years sampled. Potassium fertiliser application had no effect on foliar magnesium concentrations during this study, although for the 400 kg K/ha treatment there was a significant ($p=0.022$) increase in foliar magnesium concentration from 1997 to 1998.

Mean delta foliar magnesium was positive from 1997 to 1998, but negative from 1997 to 1999 and 1997 to 2002. There were no significant treatment effects on delta foliar magnesium (Fig. 4). This suggests that environmental factors, and/or differences in sampling and analysis, may be influencing the outcome and not fertiliser application in this marginally magnesium-deficient stand.

Foliar potasssium

Foliar potassium concentrations in the control treatment were very high over the 5.5 years of sampling, ranging from 0.99% to 1.22% compared to the critical potassium concentrations of 0.3–0.5% (Will 1985). Potassium fertiliser application had no significant effect on foliar potassium concentrations in the first and third years after fertiliser

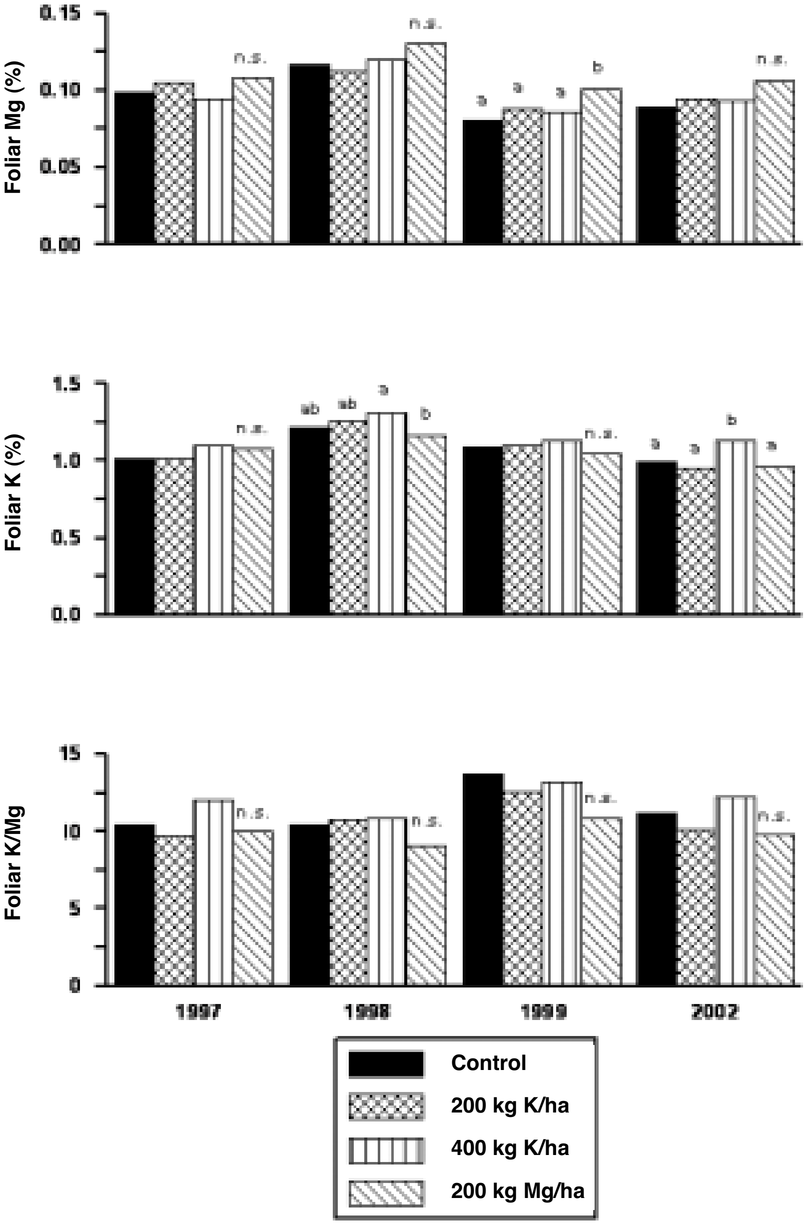

FIG. 3–Foliage magnesium and potassium concentrations and K/Mg concentration ratios at northern Kaingaroa Forest. Means with the same letter are not significantly different at p=0.1; n.s. = no significant difference between treatment means at p=0.1.

application (Fig. 3). In the second year there was a small but significant (p=0.053) increase in foliar potassium concentrations at the high rate of potassium application compared to the control treatment. Only in 2002, 5.5 years after application, was there a strongly significant

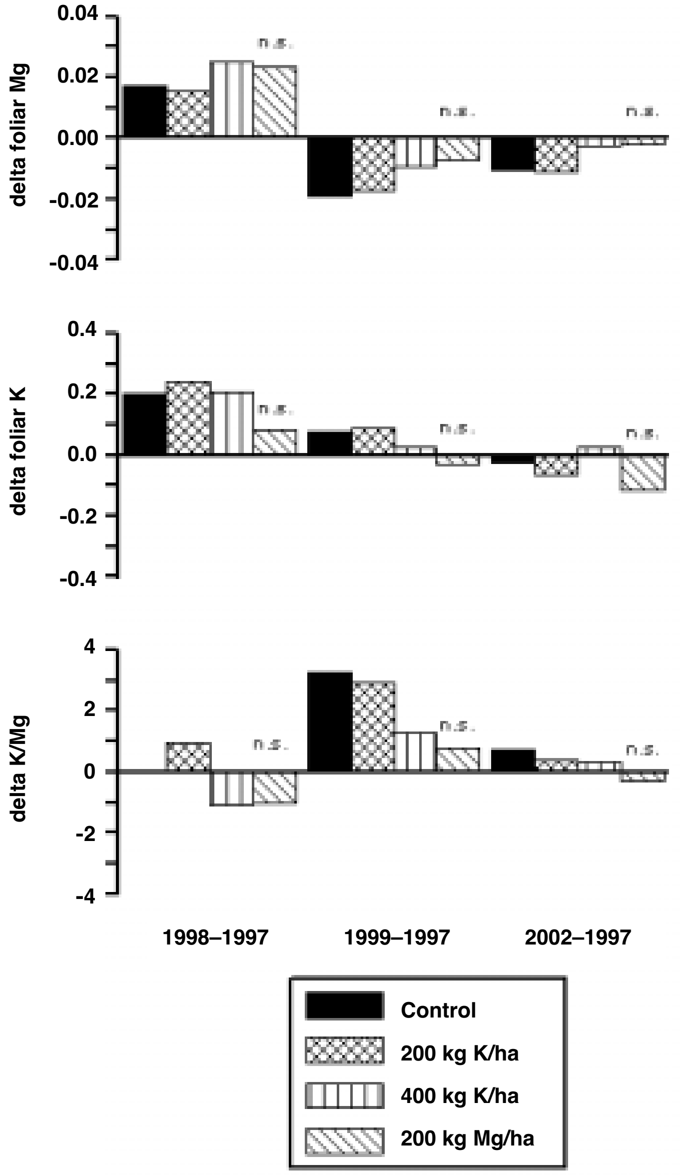

FIG. 4 –Changes in foliar magnesium and potassium concentrations and K/Mg concentration ratios from 1997 to 2002 (e.g., delta foliar magnesium concentration = 2002, 1999, or 1998 foliar magnesium concentration minus 1997 foliar magnesium concentration) at northern Kaingaroa Forest; n.s. = no significant difference between treatment means at p=0.1.

(p=0.003) increase in foliar potassium concentrations compared to the control treatment at the high rate of potassium application. As was found for foliar magnesium, there were no consistent trends in the changes in foliar potassium concentrations between the different years sampled. Potassium fertiliser at 200 kg K/ha appears to have significantly (p=0.013) increased foliar potassium concentrations from 1997 to 1998. Environmental factors probably had a greater influence on changes in foliar potassium concentrations between the different years sampled, as there was a significant (p<0.001) decrease in foliar potassium concentrations across all treatments from 1998 to 1999. Magnesium fertiliser application had no effect on foliar potassium concentrations during this study.

Mean delta foliar potassium values followed similar trends to those for delta foliar magnesium. As for delta foliar magnesium, there were no significant treatment effects on delta foliar potassium concentrations (Fig. 4).

Foliar K/Mg

In spite of significant changes in soil solution and exchangeable K/Mg ratios due to magnesium and potassium fertiliser application early on in the experiment (Fig. 1 and 2), in the 5.5 years after fertiliser application there were no significant responses to the fertiliser treatments (Fig. 3). There was, however, a general trend of lower foliar K/Mg concentration ratios in the trees treated with magnesium than in the control treatment. There were no significant year effects on foliar K/Mg ratios. As was found for delta foliar magnesium and potassium, there were no significant treatment effects on delta foliar K/Mg ratios (Fig. 4).

Effect of Magnesium and Potassium fertilisers on UMCY Values

In 1997 and 2001, UMCY values in the control treatment ranged from 1 to 6. This equated to healthy upper crowns (A+) through to hollow zone caused by death of secondary branches occupying more than half the width of the upper crown (C-) (Fig. 5a). While it was not expected that the application of magnesium and potassium fertilisers would affect UMCY values in 1997, there was a significant treatment effect in 2001. Magnesium

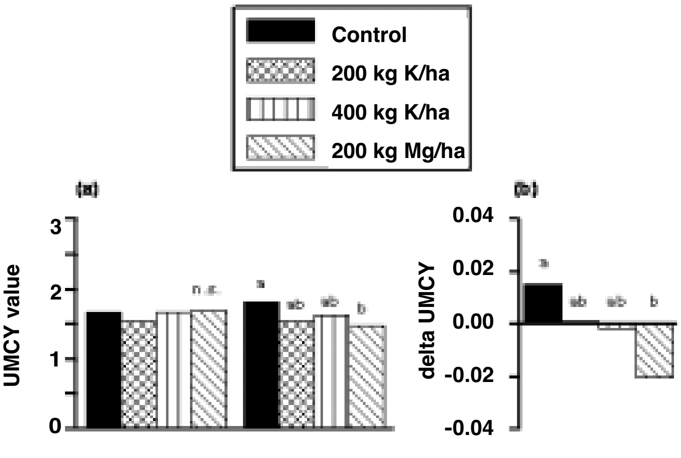

FIG. 5–(a) UMCY values in 1997 and 2001, and (b) change in UMCY values from 1997 to 2001 (delta UMCY value = 2001 UMCY minus 1997 UMCY value), calculated for individual trees and averaged for the respective plots at northern Kaingaroa Forest. Means with the same letters are not significantly different at p=0.1; n.s. = no significant difference between treatment means at p=0.1.

fertiliser application significantly (p=0.074) decreased UMCY values compared to the control treatment.

The reduction in UMCY values in the magnesium-treated plots was reflected in delta UMCY analysis. A significant (p=0.055) decrease in UMCY value was recorded from 1997 to 2001 for the magnesium fertiliser treatment compared to the control treatment (Fig. 5b).

The changes in UMCY value between the 2 years of measurement were associated with changes in foliar magnesium and potassium concentrations and K/Mg ratios (Fig. 6).

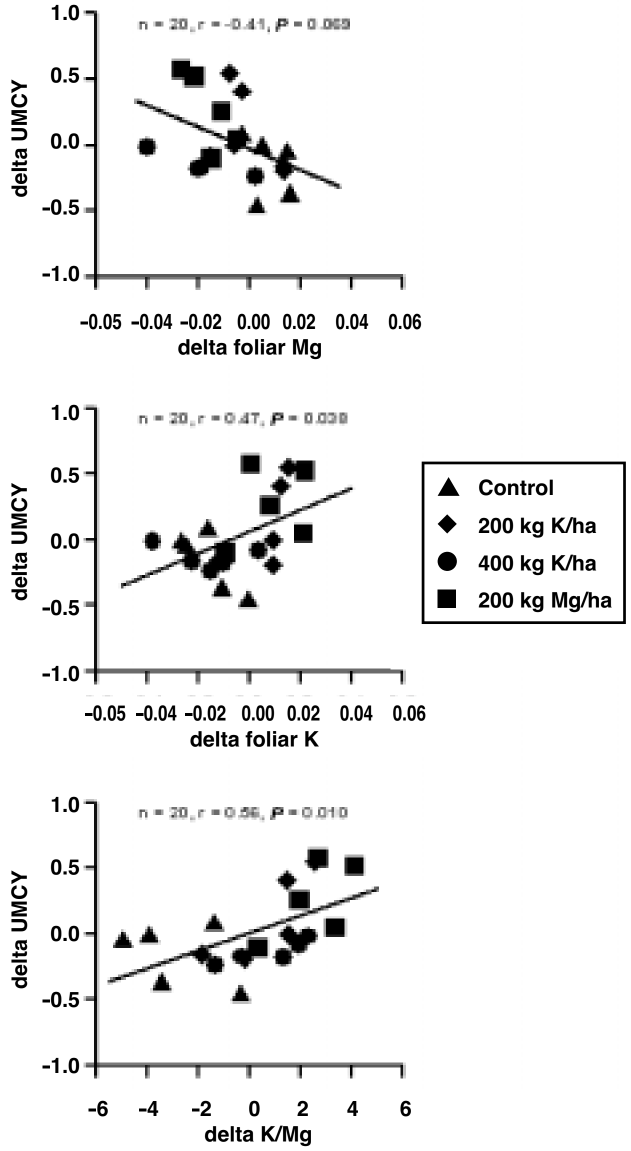

FIG. 6–Relationships between delta UMCY and delta foliar magnesium, potassium, and K/Mg at northern Kaingaroa Forest.

Increases in UMCY value were negatively correlated with increases in foliar magnesium and positively correlated with increases in foliar potassium and foliar K/Mg ratio.

DISCUSSION

This study showed that a range of soil-exchangeable K/Mg ratios (0.2–2.5) and solution-equivalent K/Mg ratios (0.4–8.5) could be obtained in the 0–10 cm soil depth at this site by the application of magnesium and potassium fertilisers. Magnesium fertiliser application decreased these ratios as a result of increases in soil-exchangeable and soil-solution magnesium concentrations, and potassium fertiliser application increased these ratios by increasing soil-exchangeable and solution potassium concentrations.

Olykan *et al.* (2001) reported that the soil-exchangeable K/Mg ratio in the 0–10 cm depth of Pumice Soils under *P. radiata* at Tauhara Forest (central North Island) remained significantly lower than in the control treatment even 10 years after the application of dolomite at the rates of 55 and 400 kg Mg/ha. Hunter (1996) also reported a significant increase in exchangeable magnesium (control treatment value of 0.1 $cmol_{(+)}$/kg *versus* 0.33 $cmol_{(+)}$/kg for magnesim fertiliser treatment) in the 0–10 cm soil depth 5 years after application of magnesium fertiliser (75% dolomite, 25% Epsom salts) at the rate of 100 kg Mg/ha to 6-year-old *P. radiata* at Dry Fly Road, southern Kaingaroa Forest.

In spite of improvements in the magnesium nutritional status of the soil at the northern Kaingaroa trial site recorded during the first 18 months of this study, in the 5 years after magnesium fertiliser application only an episodic small increase in foliar concentrations of magnesium and a decrease in foliar K/Mg ratios were recorded. These foliar concentrations did not reflect the significant changes that occurred in magnesium concentrations in soil-solution and soil-exchangeable magnesium, and K/Mg ratios. No firm critical concentrations for soil-exchangeable and solution magnesium have been reported. Will (1961) suggested a critical exchangeable magnesium concentration of 0.2 $cmol_{(+)}$/kg and research by Sun & Payn (1999) suggested a critical concentration of 0.04 mmol/litre for solution magnesium concentration. Exchangeable-magnesium (0.6 $cmol_{(+)}$/kg) and solution-magnesium (0.05 mmol/litre) concentrations in the control plots were above these suggested critical concentrations but the trees at northern Kaingaroa have displayed UMCY symptoms, suggesting either that critical levels are higher than those previously reported or that there were other factors such as nutrient antagonisms, tree genetics, potassium and magnesium status of subsoil, periods of low rainfall, or interactions between these factors causing UMCY symptoms. Interestingly, the seasonal fluctuations in foliar magnesium were, on average ($p<0.0001$), greater than the fertiliser effects (Fig. 4).

In contrast to this study, other studies have reported dramatic improvements in the magnesium status of *P. radiata* after application of magnesium fertiliser. Hunter (1996) reported that the application of 100 kg Mg/ha to highly magnesium-deficient 6-year-old *P. radiata* (foliar Mg 0.03%) at Dry Fly Road in southern Kaingaroa Forest increased foliar magnesium from 0.04% to 0.06% 18 months after magnesium application, and this level remained constant at 0.11% from the third to the seventh year. Payn (1991) found that the application of Epsom salts at the rate of 400 kg Mg/ha to 6-year-old *P. radiata* at Tauhara Forest significantly increased foliar magnesium concentration from 0.074% to 0.101% 6 months after fertiliser application. In a similar experiment at southern Kaingaroa Forest, the same treatment applied to 6-year-old *P. radiata* significantly increased foliar magnesium concentration from 0.047% to 0.089% 6 months after fertiliser application (Payn 1991). Hunter *et al.* (1986) reported that 6-year-old trees in Kaingaroa Forest with extremely deficient foliar magnesium concentrations of 0.02–0.03% responded to the application of 100 kg Mg/ha (a mixture of 25% Epsom salts and 75% dolomite) and foliar magnesium was elevated to 0.085% over the next 2.5 years.

Longer-term responses to magnesium fertiliser additions have also been found. Hunter (1996) reported significant improvements in foliar magnesium 5 years after the application of 150 and 400 kg Mg/ha to young trees with deficient foliar magnesium concentrations of 0.06% at Tauhara Forest. Olykan *et al.* (2001) showed that this response was sustained when reporting significant increases in foliar magnesium nutrition, and decreases in foliar K/Mg ratios, 10 years after application. The greatest improvement in foliar magnesium nutrition, 0.14%, was recorded at the highest rate of magnesium addition.

The major differences between the response to magnesium fertiliser recorded by the above workers and that reported in this study at northern Kaingaroa Forest were the magnesium status of the control treatment soils, the considerably younger stand age at fertiliser application, and the low concentrations of foliar magnesium prior to fertiliser addition in the trials conducted previously. The exchangeable-magnesium concentration of soils (0–10 cm) at the Tauhara Forest trial of Olykan *et al.* (2001) was 0.19 $cmol_{(+)}$/kg which is much lower than the value of 0.6 $cmol_{(+)}$/kg at northern Kaingaroa Forest. The soil-exchangeable K/Mg ratio was also higher at Tauhara trials (1.77) than at the northern Kaingaroa Forest trial (<1). Therefore, magnesium fertiliser had a stronger effect on the foliar magnesium concentration at Tauhara Forest than at northern Kaingaroa Forest. At northern Kaingaroa Forest, magnesium and potassium fertilisers were applied late in the mid-rotation phase, at a stand age of 20 years. A better response may be expected in younger trees such as those used in the trials of Hunter *et al.* (1986), Payn (1991), and Olykan *et al.* (2001), which were probably growing at a faster rate than a maturer stand such as that at northern Kaingaroa Forest. Other studies have also reported slow and/or poor responses by older *P. radiata* trees to elevated soil magnesium concentrations through magnesium fertiliser (Hunter 1996; Mitchell *et al.* 1999).

In the Tauhara Forest trial it was noted that the concentration of foliar magnesium in the control treatment increased from 0.067% in 1990 (Hunter 1996) to 0.108% in 1994 (Olykan *et al.* 2001). While the reasons for this, and for the lack of response of the northern Kaingaroa Forest trial to fertiliser treatments, are not known, the recycling of magnesium from the decomposition of the understorey and the litter layer, as well as internal retranslocation in mature stands, would have also contributed to the magnesium nutrition of the trees.

Mean foliar magnesium concentration for the control treatment at northern Kaingaroa Forest in the samples collected in 2002 was 0.089%, just below the critical concentration of 0.1% reported by Will (1985). Foliar magnesium concentration for the magnesium treatment (200 kg Mg/ha) at 0.101% was slightly higher and a K/Mg ratio of 9.8 was only 1.3 lower than that in the control treatment. By comparison, mean foliar magnesium concentration for the no-fertiliser control treatment at the Tauhara Forest trial as reported by Olykan *et al.* (2001) was 0.108% and the K/Mg ratio was 9.8 — these values were respectively higher and lower than those recorded at northern Kaingaroa Forest. In the treatment that resulted in the greatest response at the Tauhara Forest trial (dolomite fertiliser treatment at 400 kg Mg/ha), the mean foliar magnesium concentration was 0.132%, an increase of 0.024% compared to the control treatment, and the K/Mg ratio decreased by 2.1 to 7.7. Considering the rate of magnesium fertiliser addition and the age of the trees at northern Kaingaroa Forest, the changes recorded in foliar magnesium concentrations and foliar K/Mg ratios are consistent with those reported by Olykan *et al.* (2001) for the reasons given in the preceding paragraph.

Because of the apparent slow response of *P. radiata* to magnesium fertiliser additions in older stands where foliar magnesium is initially marginal rather than deficient, maintaining elevated soil magnesium levels in the longer-term may be more important than the actual magnitude of the increase in foliar magnesium concentration after fertiliser application. Increases in concentrations of soil-solution and exchangeable magnesium, and decreases in soil-solution and exchangeable K/Mg ratios, were maintained over the 2 initial years of sampling. However, whether these changes are maintained in the longer-term is unknown. Similar increases in soil-solution and exchangeable magnesium, and decreases in soil-solution and exchangeable K/Mg ratios, were recorded at two other *P. radiata* trials on Pumice Soils also located in Kaingaroa Forest 2 years after the application of calcined magnesite fertiliser at 150 kg Mg/ha (Mitchell *et al.* 1999). Further research is needed into the long-term impacts of magnesium fertiliser on a range of soil types before any firm conclusions can be drawn as to whether magnesium fertiliser treatment can maintain high concentrations of soil magnesium through a complete rotation and into subsequent rotations. The significant reductions in soil-solution and exchangeable magnesium in the second year of sampling in this trial suggest that the impact of magnesium fertiliser addition on plant-available magnesium in the 0–10 cm soil layer at this site may be short-lived.

This study showed no consistent improvements in foliar magnesium nutrition nor reduced K/Mg ratios, in response to magnesium fertiliser additions. In addition, the application of potassium fertiliser had little effect on foliar potassium nutrition and no effect on the K/Mg ratio. Therefore, it was unlikely that a significant effect of these fertilisers on UMCY values would be observed in the medium term. However, magnesium fertiliser treatment significantly decreased UMCY values and the change in UMCY score from 1997 to 2001, compared to the control treatment, was a positive result. Research suggests that the foliar K/Mg ratio may be important in determining whether a stand will develop UMCY (Beets & Jokela 1994). Current foliar recommendations suggest that if foliar K/Mg ratios are above 10, UMCY will be present or is likely to develop depending on the age of the stand (Olykan *et al.* 2001). At northern Kaingaroa Forest the mean foliar K/Mg ratio in the control treatment in 2002 was 11.1 and the addition of magnesium fertiliser at 200 kg Mg/ha only reduced it to 9.8. These K/Mg values corresponded to mean UMCY values in 2001 of 1.85 and 1.51 respectively. In contrast, at the Tauhara trial (Olykan *et al.* 2001), 10 years after application of 150 and 400 kg Mg/ha the K/Mg ratios were significantly reduced from 9.8 in the control treatment to 7.7 and 6.1 respectively, and the UMCY values were significantly reduced from the control treatment value of 2.55 to 1.74 and 1.60 for the lower and higher magnesium rates respectively.

In a magnesium fertiliser trial in the same stand as the northern Kaingaroa Forest trial, the UMCY value was significantly reduced 6 years after the application of 150 kg Mg/ha as calcined magnesite (Forest Research unpubl. data). While this confirms that magnesium fertiliser additions can be effective in reducing UMCY in older stands, it appears that the age of trees is an important factor controlling the foliar magnesium and UMCY responses to magnesium fertiliser application. Also, the magnesium status of the trees at the time of fertiliser application, and those factors controlling the subsequent risk of UMCY development, are important.

Potassium fertiliser application, even at double the rate of magnesium fertiliser application, had no effect on the change in UMCY value from 1997 to 2001, unlike magnesium fertiliser application. However, the significant ($p=0.038$) relationship between the change in UMCY and the change in foliar potassium (Fig. 6) suggests that the application of potassium fertiliser may have influenced UMCY values at northern Kaingaroa Forest. Even so, a closer inspection of the data presented in Fig. 6 indicates that factors other than fertiliser application, such as rainfall and foliage sampling, may be influencing changes in foliar potassium concentrations and changes in UMCY values.

Another reason for the fertiliser application having very little effect on foliar nutrient concentration, despite having significant effects on soil potassium and magnesium concentrations in the topsoil (0–10 cm), is that the tree roots may be taking up potassium from deeper soil layers in these Pumice Soils which may have potassium-rich lapilli layers of variable thickness (Beets *et al.* in press). Will & Knight (1968) sampled Kaingaroa silty sand by layers (horizons) to a depth of 2.5 m and grew *P. radiata* seedlings in a pot trial using the different soil horizons as the medium. They found differences in the potassium and magnesium supply from the different layers. The three layers of Taupo pumice below the topsoil had low levels of magnesium but high levels of potassium, while a buried soil at 2.4 m had a limited potassium supply but provided a good source of magnesium. The results of both of these studies highlight the need to consider the effect of soil chemistry below the topsoil, especially in soils of volcanic origin where rooting depths are not impeded.

Genetic variation between seedlings planted at northern Kaingaroa Forest and other trials may be responsible for the contrasts in UMCY values, the corresponding foliar K/Mg ratios, and the response to fertiliser application, as well as variation in response to treatments within a trial. Genetic variations have been reported as a cause for the foliar magnesium concentration differences and, therefore, foliar K/Mg ratios of *P. radiata* trees exhibiting UMCY symptoms (Beets & Jokela 1994). Beets *et al.* (1997) reported that variation in genotypic resistance to UMCY was at least 64%, which was high enough to support a future role for clonal forestry in the management of high-risk sites.

CONCLUSIONS

Kieserite, a soluble magnesium fertiliser applied to a Pumice Soil under 20-year-old *P. radiata* at a rate of 200 kg Mg/ha, increased soil-solution and exchangeable magnesium and reduced soil-solution and exchangeable K/Mg ratios in the top 10 cm of soil during the first 2 years after fertiliser application. Potassium sulphate, a soluble potassium fertiliser, applied at 200 kg K/ha and 400 kg K/ha significantly increased soil-solution and exchangeable K/Mg ratios in the 2 years, but only the increase due to potassium fertiliser at 400 kg K/ha was significant for exchangeable potassium and the K/Mg ratio for both years of sampling. These results show that the exchangeable K/Mg balance in the surface Pumice Soils can be significantly amended by the application of potassium and magnesium fertilisers, and the changes can be maintained for over 18 months. However, continued monitoring of the soil is required to establish whether changes can be maintained over a complete rotation of *P. radiata* and beyond.

The application of kieserite and potassium sulphate, in spite of significantly increasing solution and exchangeable magnesium and potassium and amending the K/Mg ratios in the 0–10 cm soil layer, did not result in any conclusive changes in the magnesium and potassium nutrition based on treatment means, whether the individual years or the changes between years were considered in the foliage of the 20-year-old *P. radiata*. The high rate of potassium fertiliser application (400 kg K/ha) significantly increased foliar potassium concentrations only in the last year (2002) of sampling, 5.5 years after addition. Magnesium fertiliser application significantly increased foliar magnesium concentrations only in the third year (1999) of sampling. Magnesium or potassium fertiliser application did not affect UMCY values in 1997, but UMCY values and the change in UMCY value from 1997 to 2001 were significantly lower for the magnesium treatment than for the control treatment. Potassium fertiliser application did not directly affect the UMCY values in 1997 and 2001 or the change in UMCY value between the 2 years. However, correlation analysis suggests that increases in foliar potassium concentrations due to fertiliser application were related to increases in UMCY values.

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REFERENCES

BALLARD, R. 1978: Effect of slash and soil removal on the productivity of second rotation radiata pine on a pumice soil. *New Zealand Journal of Forestry Science 8*: 248–258.

BARBER, S.A. 1984: “Soil Nutrient Bioavailability — A Mechanistic Approach”. John Wiley and Sons Inc., New York, USA.

BEETS, P.N.; JOKELA, E.J. 1994: Upper Mid-Crown Yellowing in *Pinus radiata*: Some genetic and nutritional aspects associated with its occurrence. *New Zealand Journal of Forestry Science 24*: 35–50.

BEETS, P.N.; OLIVER, G.R.; KIMBERLEY, M.O. 1997: Genotypic variation in symptoms of Upper Mid-Crown Yellowing and *Cyclaneusma minus* in a *Pinus radiata* stand. *New Zealand Journal of Forestry Science 27*: 69–75.

BEETS, P.N.; PAYN, T.W.; JOKELA, E.J. 1993: Upper Mid-Crown Yellowing (UMCY) in *Pinus radiata* forests. *New Zealand Forestry 38*: 24–28.

BEETS, P.N.; OLIVER, G.R.; KIMBERLEY, M.O.; PEARCE, S.H.; RODGERS, B.: Genetic and soil factors associated with variation in visual magnesium deficiency symptoms in *Pinus radiata. Forest Ecology and Management* (in press).

BLAKEMORE, L.C.; SEARLE, P.L.; DALY, B.K. 1987: Methods for chemical analysis of soils. *New Zealand Soil Bureau, Scientific Report 80*.

HEWITT, A.E. 1993: "New Zealand Soil Classification". Manaaki Whenua–Landcare Research New Zealand Ltd, Lincoln, New Zealand

HUNTER, I.R. 1996: The occurrence and treatment of magnesium deficiency in radiata pine in New Zealand. *New Zealand Forest Research Institute, FRI Bulletin No. 172.*

HUNTER, I.R.; PRINCE, J.M.; GRAHAM, J.D.; NICHOLSON, G.M. 1986: Growth and nutrition of *Pinus radiata* on rhyolitic tephra as affected by magnesium fertiliser. *New Zealand Journal of Forestry Science 16(2)*: 152–165.

HUNTER, I.R.; RODGERS, B.E.; DUNNINGHAM, A.; PRINCE, J.M.; THORN, A.J. 1991: An atlas of radiata pine nutrition in New Zealand. *New Zealand Forest Research Institute, FRI Bulletin No. 165.*

MACLAREN, J.P. 1993: Radiata pine growers' manual. *New Zealand Forest Research Institute, FRI Bulletin No. 184.*

MENGAL, K.; KIRKBY, E.A. 1987: "Principles of Plant Nutrition". 4th edition. International Potash Institute, Bern, Switzerland.

MITCHELL, A.D. 2000: Magnesium fertiliser effects on forest soils under *Pinus radiata*. Ph.D. thesis, Massey University, Palmerston North, New Zealand.

MITCHELL, A.D.; LOGANATHAN, P.; PAYN, T.W.; TILLMAN, R.W. 1999: Effect of calcined magnesite on soil and *Pinus radiata* foliage magnesium in pumice soils of New Zealand. *Australian Journal of Soil Research 37*: 545–560.

NICHOLSON, G. 1984: Methods of soil, plant, and water analysis. *New Zealand Forest Service, FRI Bulletin No. 70.*

OLYKAN, S.; PAYN, T.; BEETS, P.; KIMBERLEY, M. 2001: Magnesium fertilisers affected growth, upper mid-crown yellowing, and foliar nutrients of *Pinus radiata* and soil magnesium concentration. *New Zealand Journal of Forestry Science 31*: 34–50.

PAYN, T.W. 1991: The effects of magnesium fertiliser and grass on the nutrition and growth of *P. radiata* planted on pumice soils in the central North Island of New Zealand. Ph.D. thesis, University of Canterbury, New Zealand.

PAYN, T.W.; MEAD, D.J.; WILL, G.M.; HUNTER, I.R. 1995: Magnesium nutrition and dry matter allocation patterns in *Pinus radiata*. *New Zealand Journal of Forestry Science 25*: 39–48.

SAS INSTITUTE 1996: "Generalised Linear Modelling (GLM) Procedure", version 6.12. SAS Institute Inc, Cary, NC.

SUN, O.J.; PAYN, T.W. 1999: Magnesium nutrition and photosynthesis in *Pinus radiata*: clonal variation and influence of potassium. *Tree Physiology 19*: 535–540.

WILL, G.M. 1961: Magnesium deficiency in pine seedlings growing in pumice soil nurseries. *New Zealand Journal of Agricultural Research 4*: 151–160.

———1966: Magnesium deficiency: the cause of spring needle-tip chlorosis in young pines on pumice soils. *New Zealand Journal of Forestry 20*: 243–253.

———1985: Nutrient deficiencies and fertiliser use in New Zealand exotic forests. *New Zealand Forest Service, FRI Bulletin No. 97.*

WILL, G.M.; KNIGHT, P.J. 1968: Pumice soils as a medium for tree growth. II. Pot trial evaluation of nutrient supply. *New Zealand Journal of Forestry 13*: 50–65.